EXPERIMENTAL MODELING AND CONTROL OF THE HYDRAZINE-OXYGEN FUEL CELL

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ABSTRACT

Fuel cells are direct energy conversion devices which produce direct current electrical power. They are being considered for use in many modern power applications such as spacecraft, vehicular propulsion, and general purpose electrical power. The hydrazine-oxygen fuel cell is one of several types, and its operation is described. Some parameters of the chemical inputs, such as oxygen source pressure, are experimentally tested and discussed as candidates for controlling the output voltage. A control parameter is selected, and a mathematical model of the fuel cell is developed. A "Fuel Cell Research System", designed and constructed by the author, is described and operating instructions are presented.

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TABLE OF SYMBOLS AND ABBREVIATIONS

G_{FC}	Fuel cell transfer function
S	LaPlace transform operator
e	Natural logarithm base
P	Pole of a function
z	Zero of a function
T_{FC}	Fuel cell operating temperature
P_o	Oxygen source pressure, pure oxygen input
P_A	Oxygen source pressure, air input
P_H	Hydrogen fuel pressure
F_o	Oxygen source flow rate
F_H	Hydrogen fuel flow rate
γ_o	Per cent oxygen in oxygen source
γ_H	Per cent hydrazine in hydrogen fuel
γ_E	Per cent electrolyte in hydrogen fuel
B_p	The psig value at which a sinusoidal input pressure is biased (for frequency analysis)
A_p	The psig amplitude of a sinusoidal input pressure (for frequency analysis)
α	Fuel cell time delay constant
t_{po}	The time the air pressure input is zero while the hydrazine fuel pressure is at the normal circulating value (used in time delay analysis)(seconds).
t_d	Fuel cell system delay time (seconds)
R_L	Fuel cell resistive load
R_g	Fuel cell internal resistance
E	Fuel cell open circuit voltage
I	Fuel cell load current
W	Fuel cell power output
KOH	Chemical formula for potassium hydroxide
N_2H_4	Chemical formula for hydrazine
ml	Milliliters
psig	Pounds per square inch (gage)
CPS	Cycles per second

EXPERIMENTAL MODELING AND CONTROL

OF THE

HYDRAZINE-OXYGEN FUEL CELL

1. Definition and Applications

The principle of operation of a fuel cell was known as early as 1839 when W. R. Grove conducted experiments on what would today be called a fuel cell. [1] Until recently, obtaining electrical power from a fuel cell was an inefficient process which suffered in comparison with the steam cycle and the internal combustion engine. The Gemini spacecraft used fuel cells as an electrical power source, and fuel cell technology has improved as a result of the success of this application. [12] Smog has been settling over our cities, and the cry to eliminate the internal combustion engine in favor of electric propulsion systems has been increasingly heard. Thus, the fuel cell emerges today as a hero of the space program and a potential savior for our smog-ridden cities. In addition to these more publicized applications, fuel cells are being considered for use in military transportation in both land and ocean environments. [12] In particular, the Navy is conducting experiments to determine the adaptability of a fuel cell to the high pressures which would be encountered if used to power a deep submersible.

The fuel cell is a member of the class of devices known as direct energy conversion systems. Solar cells and heat cells are other examples. [8] Direct energy conversion implies that energy is obtained from an energy source without having to go through an intermediate process such as a heat cycle or mechanical energy conversion. The fuel cell is an electro-chemical device in which the chemical energy of a fuel is directly converted into low voltage, direct current energy. [9]

In a conventional electric battery, chemical energy is used to produce electrical energy. In this case, the anode and the cathode take part in the reaction and are gradually consumed until the battery is no longer useful. A fuel cell employs much the same principle as the

battery, but its anode and cathode are nonconsumable. The fuel required to sustain the chemical reaction is supplied continuously to the electrodes from an outside source, just as gasoline is fed to the internal combustion engine by means of a fuel pump. [12]

A fuel cell propulsion system driving an electric motor would have a fuel tank. Instead of pulling up to a gas station, one might pull his quiet, clean, and light electric car up to a hydrogen station, or to a hydrazine station. All fuel cell fuels are basically hydrogen sources. This hydrogen reacts with oxygen from the air or an oxygen source, and produces water, heat, electrical energy and other by-products depending on the fuel used.

The primary drawback of present fuel cell operation is the cost of the best fuels. Pure hydrogen gas, liquid hydrazine, or liquid ammonia are all good hydrogen source fuels which will operate a fuel cell at temperatures between ambient and 100 degrees centigrade and at atmospheric pressure. Unfortunately, these reactive substances are not now available at prices which would make a fuel cell system competitive with the internal combustion engine. Hydrogen sources such as the more readily available hydrocarbons are less reactive and, when used as a fuel cell fuel, require operating pressures and temperatures which become prohibitive for use in general application. [12] Studies have been made of the various fuels available, and have indicated that fuels such as hydrogen gas could become economically feasible providing the demand was sufficiently high and that the purity requirements had reasonable tolerances. [6] Other factors influence the choice of a fuel, such as ease of transportation and storage. It is not unreasonable to say that a suitable fuel can be found, and will be used to feed a fuel cell power system available for many modern applications. [12]

2. Objectives

The fuel cell is an electrical power source. It can be considered as a system which, for certain chemical inputs, produces a voltage

output. This is illustrated in Figure 1.

The objectives set forth for this experimental work are as follows:

1. Determine whether or not the output of a fuel cell power source can be effectively controlled by varying parameters of the chemical inputs.
2. Examine the parameters of the chemical inputs, such as pressure and flow rate, and comment as to which of these would be most effective in controlling the output.
3. Experimentally test the most promising of the chemical input parameters, and determine a mathematical model describing its effect on the fuel cell output.
4. Set forth various means of instrumenting a fuel cell control system, and build such a system which can be used for further research and laboratory demonstrations. Write operating instructions and laboratory procedures for operating the fuel cell system.
5. Outline further research on fuel cell systems as a logical extension of the work presented herein.

3. Physical Set-up of a Fuel Cell System

There are many types of fuel cells, usually classed by the type of fuel used, the operating pressure, and the operating temperature. A hydrazine-oxygen, low pressure, ambient temperature range fuel cell will be considered here.

The fuel cell itself consists of two porous electrodes separated by an electrolytic solution. Oxygen gas or air is pumped to one electrode, while a substance containing hydrogen in liquid or gaseous form is pumped to the other electrode. The chemical reaction takes place as the materials penetrate the porous electrodes, with ion exchange taking place through the electrolytic solution separating these electrodes. [10] This is illustrated in Figure 2. For example, the overall reaction for a hydrazine-oxygen fuel cell is:

$$N_2H_4 + O_2 \rightarrow 2H_2O + N_2 + \text{heat} + \text{electrical energy}$$

Some advantages of a fuel cell system:

1) High power per unit weight and volume
2) Quiet Operation
3) Clean Operation
4) Can operate on air
5) Byproduct is water
6) High efficiency
7) Potentially low maintenance cost
8) Long life of the unit

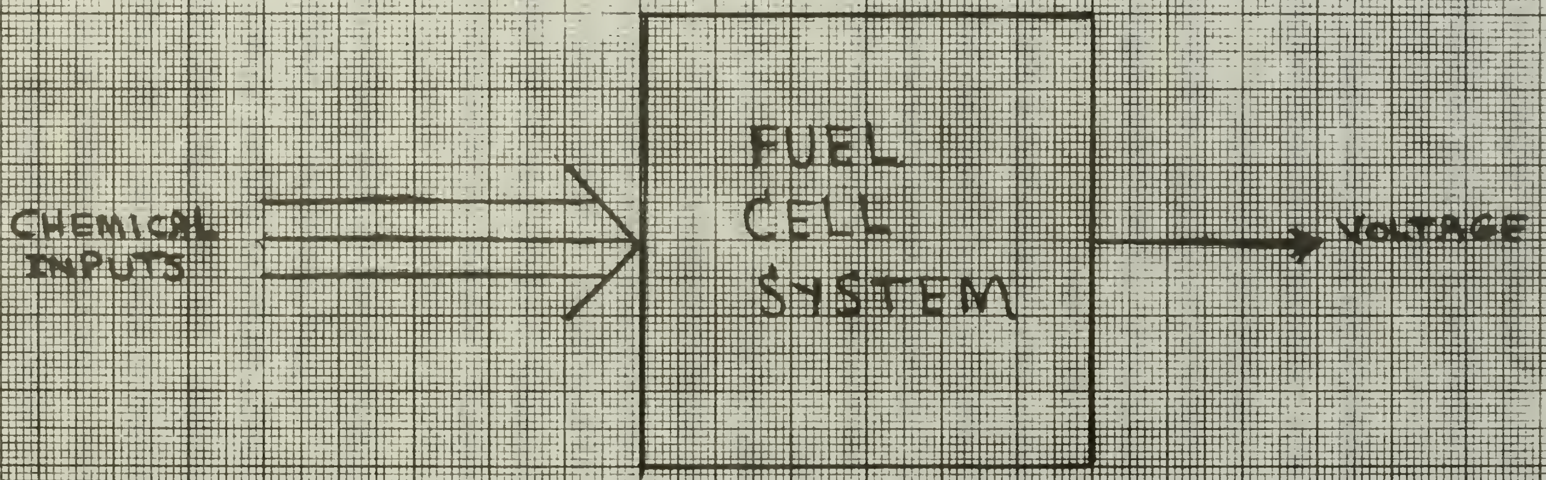


FIGURE 1

BLOCK DIAGRAM DEFINING INPUT/OUTPUT

The large arrow indicates the presence of a number of chemical inputs

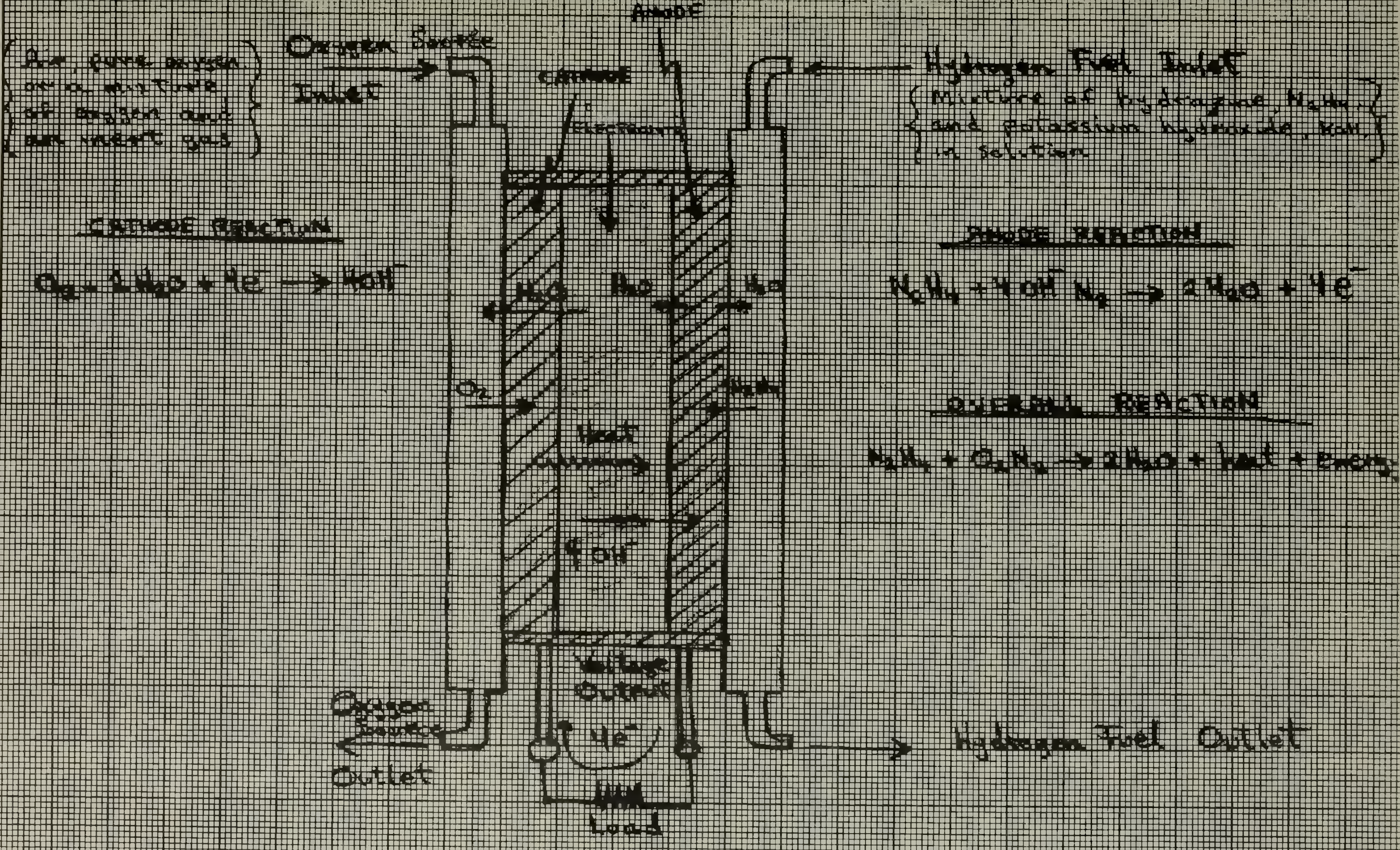


FIGURE 2
CUTAWAY VIEW OF A FUEL CELL
Showing chemical reactions for a hydrazine-oxygen fuel cell.

When an external path is provided between the electrodes, current flows and may do useful work. A typical cell might produce voltages of the order of .8 volts at power levels approaching 50 watts per square foot of effective electrode area. Effective electrode area differs from the real area by a factor which accounts for the increase of surface area due to pores and irregularities.

Externally, the fuel cell is a box having an oxygen inlet, oxygen outlet, hydrogen fuel inlet, and hydrogen fuel outlet. It may or may not have heaters for the fuel solution. Oxygen may be fed from a compressed gas source. If air is used, a compressed air source may be used, or if only low pressures are needed, a fan may suffice. The hydrogen source fuel is a mixture of liquid hydrazine (N_2H_4) and the electrolyte potassium hydroxide (KOH) in solution. It is pumped into the cell by means of an electric pump. The fuel goes through a closed cycle with the outlet returning to the fuel reservoir . The hydrogen in the fuel is used at a rate determined by the load on the cell. The closed cycle circulator also serves to carry the water produced by the chemical reaction away from the electrode area. Thus, for a liquid fuel, the solution is gradually weakened and diluted and must be periodically replaced. For a large enough bank of fuel cells, a system can power its own pump and produce electrical power very efficiently.

4. Equipment Used During Experimentation

A Model 100H hydrazine-oxygen fuel cell manufactured by Allis-Chalmers was obtained from the Naval Ordnance Test Station, China Lake, California. Various monitoring devices were obtained, and the system indicated in Figure 3 was built.

This set-up was used to obtain all of the experimental data presented. The current-to-air transducer was used to provide a sinusoidal air pressure which could be used in frequency analysis. The air pressure was biased to various values and a sinusoidal variation applied. (See Appendix IV, Part C)

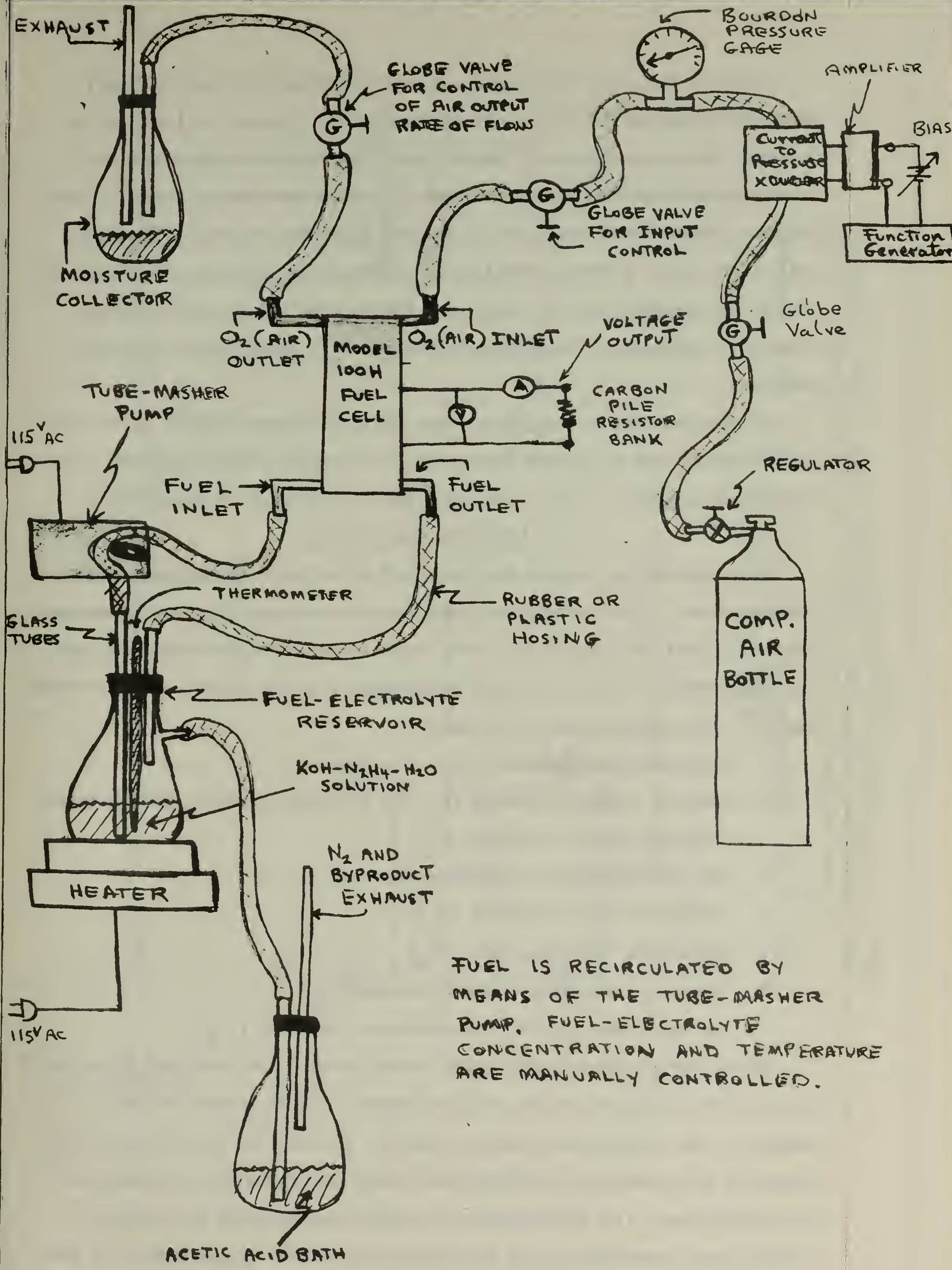

EXHAUST
GLOBE VALVE FOR CONTROL OF AIR OUTPUT RATE OF FLOW
BOURDON PRESSURE GAGE
AMPLIFIER
BIAS
Current to Pressure XDUCER
Function Generator
GLOBE VALVE FOR INPUT CONTROL
MOISTURE COLLECTOR
O_2 (AIR) OUTLET
MODEL 100H FUEL CELL
O_2 (AIR) INLET
VOLTAGE OUTPUT
Globe Valve
TUBE-MASHER PUMP
115V AC
CARBON PILE RESISTOR BANK
REGULATOR
FUEL INLET
FUEL OUTLET
THERMOMETER
RUBBER OR PLASTIC HOSING
GLASS TUBES
COMP. AIR BOTTLE
FUEL-ELECTROLYTE RESERVOIR
$KOH-N_2H_4-H_2O$ SOLUTION
N_2 AND BYPRODUCT EXHAUST
HEATER
115V AC
FUEL IS RECIRCULATED BY MEANS OF THE TUBE-MASHER PUMP. FUEL-ELECTROLYTE CONCENTRATION AND TEMPERATURE ARE MANUALLY CONTROLLED.
ACETIC ACID BATH

FIGURE 3.

Early in the experimentation, it was observed that the fuel cell was not producing the 100 watts at which it was rated. All efforts to increase the power above 30 watts failed, despite a large amount of correspondence with China Lake and Allis-Chalmers personnel. It soon became obvious that one side of the fuel cell was leaking. The fuel cell is set up in a series/parallel arrangement as indicated by Figure 3. One of the parallel pair of cells was leaking the liquid fuel solution. However, because of the parallel arrangement, some power could be obtained.

It was decided to purchase a new Allis-Chalmers Model 100H Fuel Cell System, and to build a demonstration module which could be used for further research. This was done and is described in Appendix II.

5. Modeling the System

It is desired to control the output of a fuel cell by varying some input parameter. The parameters available as an input must be determined. The best input for control will vary depending on the fuel cell type and the application. One or several parameters may be treated as controlled inputs. The choices are as follows:

1. Fuel cell temperature (T_{FC})
2. Oxygen source pressure (P_O, for oxygen input), (P_A for air input)
3. Oxygen source flow-rate (F_O)
4. Per cent oxygen in oxygen source (γ_O)
5. Hydrazine fuel pressure (P_H)
6. Hydrazine fuel flow-rate (F_H)
7. Per cent hydrazine in fuel mixture (γ_H)
8. Per cent electrolyte in electrolytic solution (γ_E)

All of the possible parameters listed above affect the rate at which the fuel cell chemical reaction takes place, and thus also cause a change in the voltage and current output. In order for the chemical reaction to be sustained, the reactants must be constantly available at the electrodes. The electrodes are usually constructed of a porous material and separated by an electrolytic solution. Flow effects of the

 = Symbol for a single fuel cell, i.e., one electrode pair.

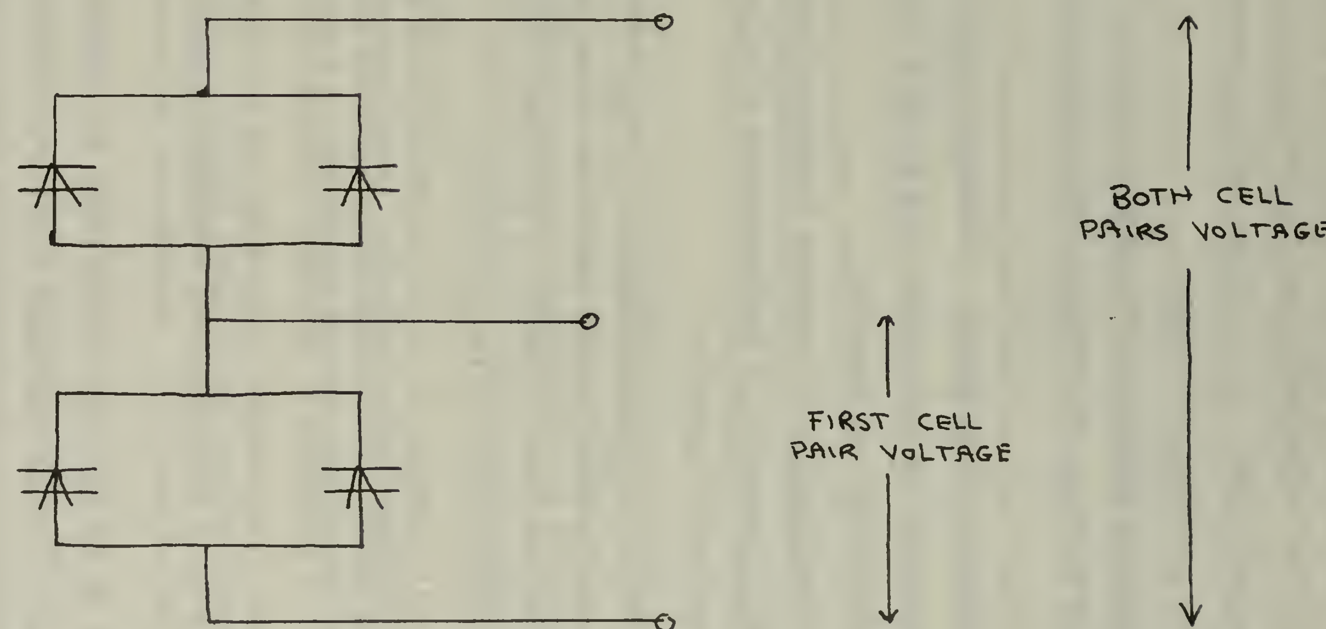


FIGURE 4

ELECTRICAL ARRANGEMENT OF MODEL 100 H FUEL BATTERY

A fuel battery is defined as an arrangement of fuel cells. However, the terms "fuel cell" and "fuel battery" are used interchangeably.

oxygen and fuel past their respective electrodes, ion flow in the electrolyte, and many other processes involving the electrodes affect the voltage and current output. [1] These various processes can be divided into four classes, as follows:

1. Activation Polarization: Processes involving the properties of electrodes in maintaining the reaction rates required for a certain output current.

2. Concentration Polarization: Processes involving the rate of arrival of reactants at the electrodes, and the rate of departure of the by-products of the chemical reaction.

3. Ohmic Polarization: Processes concerned with the electrical resistance of an electrolyte, or the resistance to passage of an ion through an electrolytic substance.

4. Polarization in Porous Electrodes: Characteristics of the reaction rate caused by using porous electrodes rather than plane electrodes. Porous electrodes are used to provide a gas/liquid interface, allowing the reactant to have access to the electrolyte.

Mathematical relations for these processes have been developed. [3], and their further study is essential for future advances in fuel cell design. It is important to be aware of these processes, but for control purposes, it is simpler to consider the fuel cell as a device having one or more of the previously mentioned control parameters and some output.

The output of the fuel cell can be taken as voltage, current, or power. If a bank of cells were used to drive an electric motor, the system could be taken to include the motor and the output could be torque or velocity. For purposes of discussion, consider the fuel cell output as a voltage. In order to study feedback control of a fuel cell, it is first desirable to establish a mathematical model of the fuel cell. The model should be for a loaded fuel cell since energy transfer is taking place under this condition. A good model would be a linearized transfer function expressed in terms of the LaPlace transform.

The fuel cell output is a voltage, and the input could be any one or more of the control parameters previously mentioned. In selecting a control parameter, the degree of controllability of each quantity must be considered. In other words, what span of outputs can be obtained for a given range of the input quantity? The various possible inputs were studied for an Allis-Chalmers Model 100H Fuel Cell System. Variables other than the one under consideration were held constant at the same values for each test.

It was necessary to establish a test procedure which would serve to keep the parameters not under study constant, and to provide the necessary data. This procedure is outlined in Appendix I. An analysis of each parameter of the fuel cell chemical inputs is presented in the following sections.

6. Fuel Cell Temperature (T_{FC})

The effect of fuel cell operating temperature on the steady state voltage output (V) is shown in Figure 5. The optimum operating temperature is about 65°C. [2]

This test, as were all tests, was made under standard conditions as defined in Appendix I. Only the parameter under study was allowed to vary.

The chemical reaction taking place in the fuel cell generates heat and will raise the operating temperature. If allowed to operate for approximately two hours, the cell temperature will rise to about 34°C. and remain near that value. [4] For this particular model, further increases in temperature must be brought about by the external addition of heat. Figure 5 shows that the output voltage changes very little for a change in temperature from 35°C. to 65°C. Also, it takes about 5 minutes to heat the fuel solution this much. Thus, for a temperature input parameter, the speed of response is slow and the span of control is small.

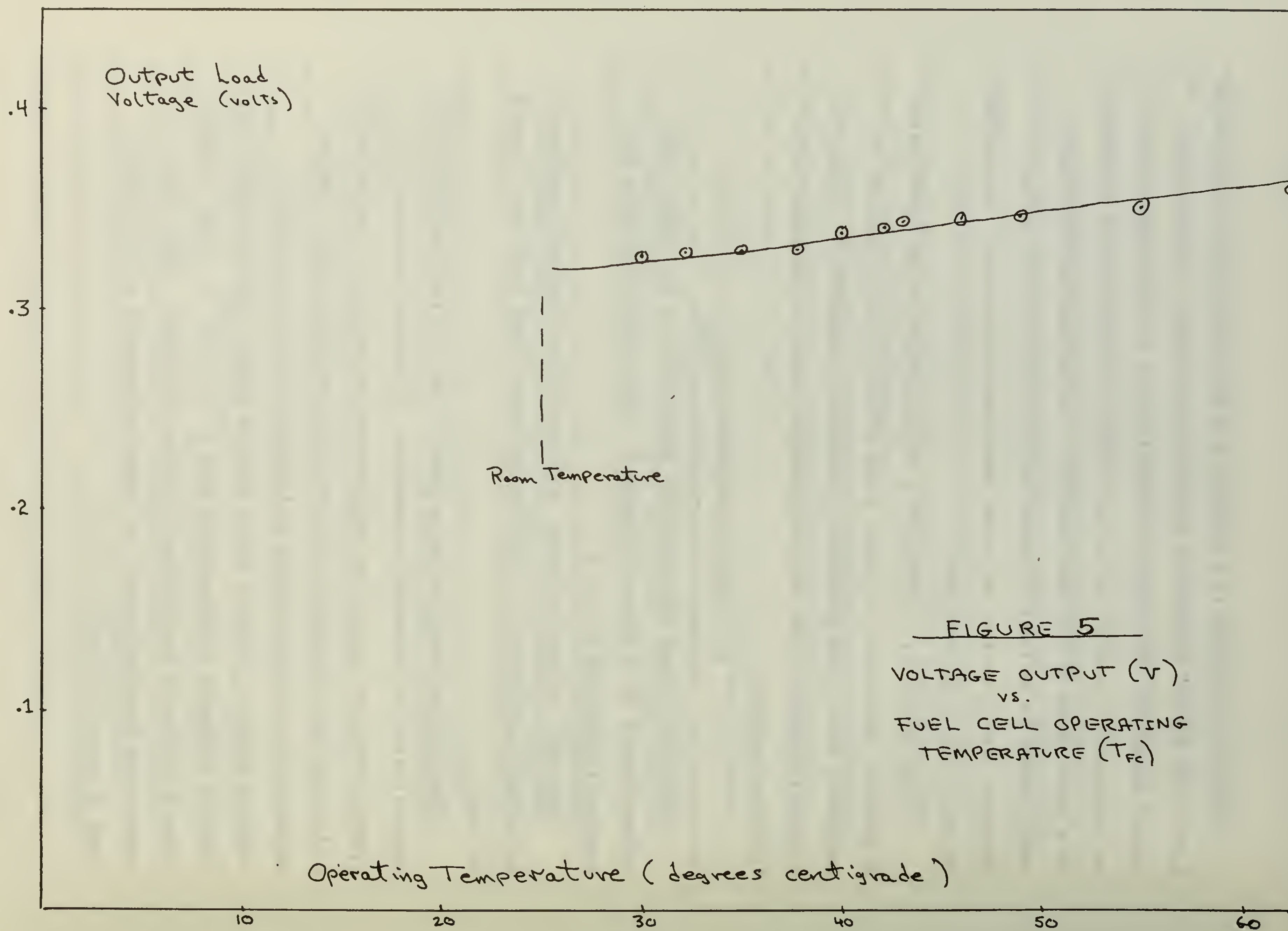


FIGURE 5

VOLTAGE OUTPUT (V)
vs.
FUEL CELL OPERATING
TEMPERATURE (T_{FC})

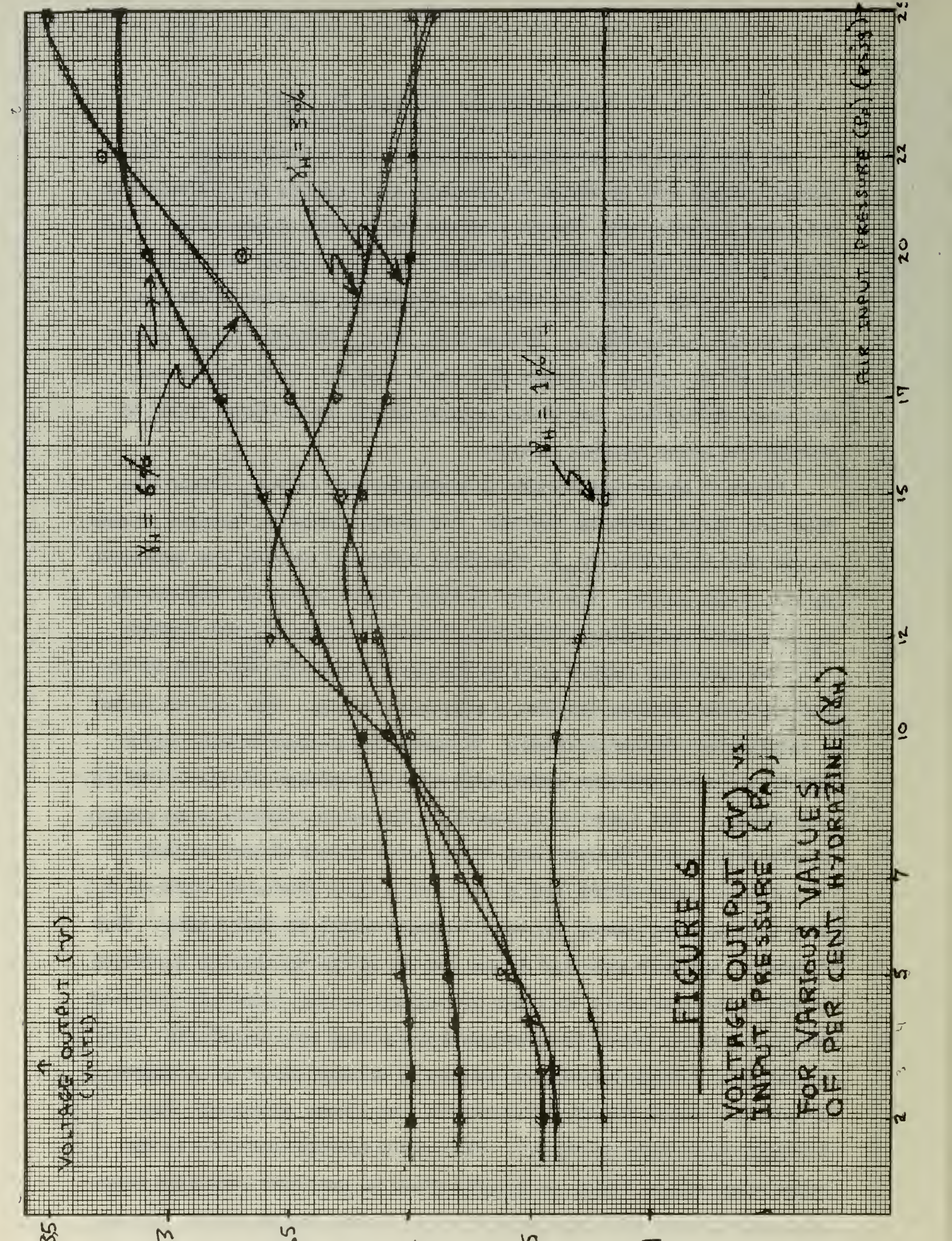
7. Oxygen Source Pressure (P_O, P_A)

Air was used as the oxygen source for these experiments. The output voltage was observed to increase non-linearly for increases in the input air pressure. Figure 6 shows the results graphically. Note that this figure shows plots of several runs made under the same conditions. It also shows the effect of decreasing per cent hydrazine (γ_H) in the fuel solution. Notice that, as γ_H decreases, the output voltage (V) vs. input pressure (P_A) curve becomes more non-linear, the slope decreases, and those regions of the curve which could be considered linear become smaller.

Figure 7 shows the results of averaging the curves, linearizing them into three operating regions, and interpolating for various values of per cent hydrazine (γ_H). The three operating regions are separated by two break points. The locus of these break points for decreasing γ_H is a good indication of how the "linear" regions become smaller.

The operating region used for frequency analysis was that for input pressures ranging between 3 psig and 12 psig. This proved to be a satisfactory operating region. It could be assumed linear, and a change of input pressure produced a good percentage change of the output voltage. The speed of response of the output voltage to an oxygen source (air) input pressure was of the order of one second or less.

Figure 7 also shows that a very small input pressure, such as 0.5 psig will produce nearly the same voltage output as will 3 psig. This "plateau" between zero and 3 psig can be called the natural operating level for the fuel cell. At these pressures, normal chemical reactions are taking place which have comparatively long time constants. Any increase of voltage above this plateau is brought about by an increase of pressure which forces the reactants into closer proximity, thus bringing about more reactions. The output voltage response in the input range above 3 psig is brought about by pressure activated chemical activity and will thus tend to vary as does the pressure. For an input of 3 psig or lower, the over-riding factor is not pressure, but rather having enough oxygen present for a normal reaction.


VOLTAGE OUTPUT (V)
(volts)
AIR INPUT PRESSURE (PA) (PSIG)
.35
.3
.25
.2
.15
.1
2
5
7
10
12
15
17
20
22
γ_H = 6%
γ_H = 3%
γ_H = 1%
FIGURE 6
VOLTAGE OUTPUT (V) vs. INPUT PRESSURE (PA),
FOR VARIOUS VALUES OF PER CENT HYDRAZINE (γ_H)

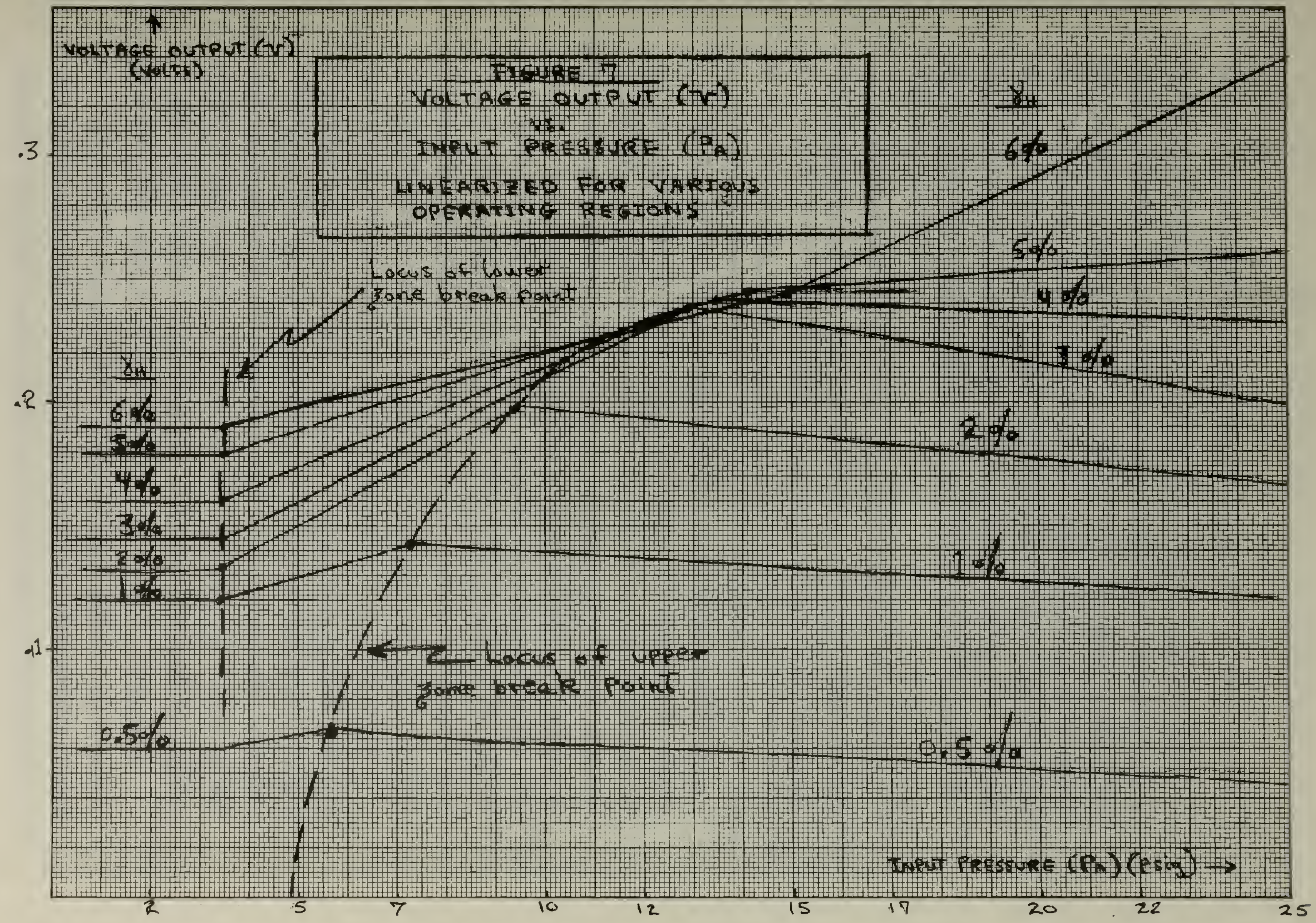


FIGURE 7
VOLTAGE OUTPUT (V)
vs.
INPUT PRESSURE (P_A)
LINEARIZED FOR VARIOUS
OPERATING REGIONS
VOLTAGE OUTPUT (V)
(VOLTS)
INPUT PRESSURE (P_A) (PSIG)
Locus of lower zone break point
Locus of upper zone break point
γ_H
6%
5%
4%
3%
2%
1%
0.5%
.3
.2
.1
2
5
7
10
12
15
17
20
22
25

8. Oxygen Source Flow Rate (F_o)

The flow rate of the oxygen source past the oxygen electrode is a good measure of the oxygen available for reaction. It can be used as a control parameter. [5] However, it was not studied during this series of experiments because of lack of monitoring equipment. It is related to the oxygen source pressure (for a given output orifice) and would have a similar effect providing that a sufficient flow rate was maintained to remove water and nitrogen products of the chemical reaction. [2]

A fuel cell system for research and demonstration has been constructed during these experiments which will provide the monitoring equipment necessary to study this parameter.

9. Per Cent Oxygen in Oxygen Source (γ_o)

Instead of using air as an oxygen source, one could use pure oxygen (O_2) mixed with some inert gas such as nitrogen (N_2). [3] By varying the amount of mixing, the per cent oxygen (γ_o) in the gas reaching the fuel cell could be changed. This would change the amount of oxygen available for reaction and thus change the output voltage (V). Actual equipment to mix gases and thus vary the amount of oxygen in the mixture sent to the fuel cell was unavailable at the time of the test. However it is possible to hypothesize the results of such a control parameter from the experiments which were conducted.

Figure 8 shows the voltage-pressure relationship for an air input and for a pure oxygen input. Notice that the oxygen input produces a curve which shows very little voltage change for any change of pressure. The oxygen input also produces a higher power level than does the air input. It is obvious that varying the input pressure (P_o) while using pure oxygen gas is not a very satisfactory control parameter.

In Figure 9, intermediate values of per cent oxygen (γ_o) have been interpolated, and the curves plotted. If a constant pressure operating line is chosen (such as line (b) at 3 psig), per cent oxygen (γ_o) can

be varied producing an output voltage change. For a certain loaded condition, Figure 9 shows that the output voltage (V) varies from zero to one volt for a per cent oxygen (γ_o) change of from zero to one hundred per cent. A curve plotting V vs. γ_o would be approximately linear for low values of γ_o, but saturating for higher values. If the constant pressure operating line were chosen at a higher value of input pressure, say 20 psig, then the curve of V vs. γ_o would change. Thus, the gain of any linearized transfer function would have a value determined by the operating line chosen.

A change in input pressure is felt at the electrode much more rapidly than would be a change in per cent oxygen. Thus, the speed of response of a system using per cent oxygen (γ_o) as a control parameter would be slower than one using air pressure (P_A). A compromise can be reached by selecting an operating line such as line (c) shown in Figure 9. Here, both P_o and γ_o are varied. This could be accomplished by having a mixer valve followed by a pressure transducer on the fuel cell oxygen source input line.

10. Hydrogen Fuel Pressure (P_H)

For a gaseous hydrogen fuel, this parameter would be more effective than it is for a liquid hydrogen fuel. The hydrogen fuel used with the Model 100H fuel cell is a mixture of 10 per cent hydrazine and 33 per cent potassium hydroxide in solution. The liquid tends to hold the hydrogen in contact with the porous electrode. Thus, the amount of hydrogen available for the chemical reaction changes very slowly as a function of the liquid fuel pressure. The liquid fuel pressure normally used for circulating the liquid fuel is 1 psig to 3 psig. Experimental observation showed that varying this pressure had only a small effect on the output voltage, and this effect was evident only after a time delay ranging from 5 to 30 seconds.

11. Hydrogen Fuel Flow Rate (F_H)

Equipment to measure flow-rates was not available at the time of the test. For a given output orifice, the flow rate is related to the fuel

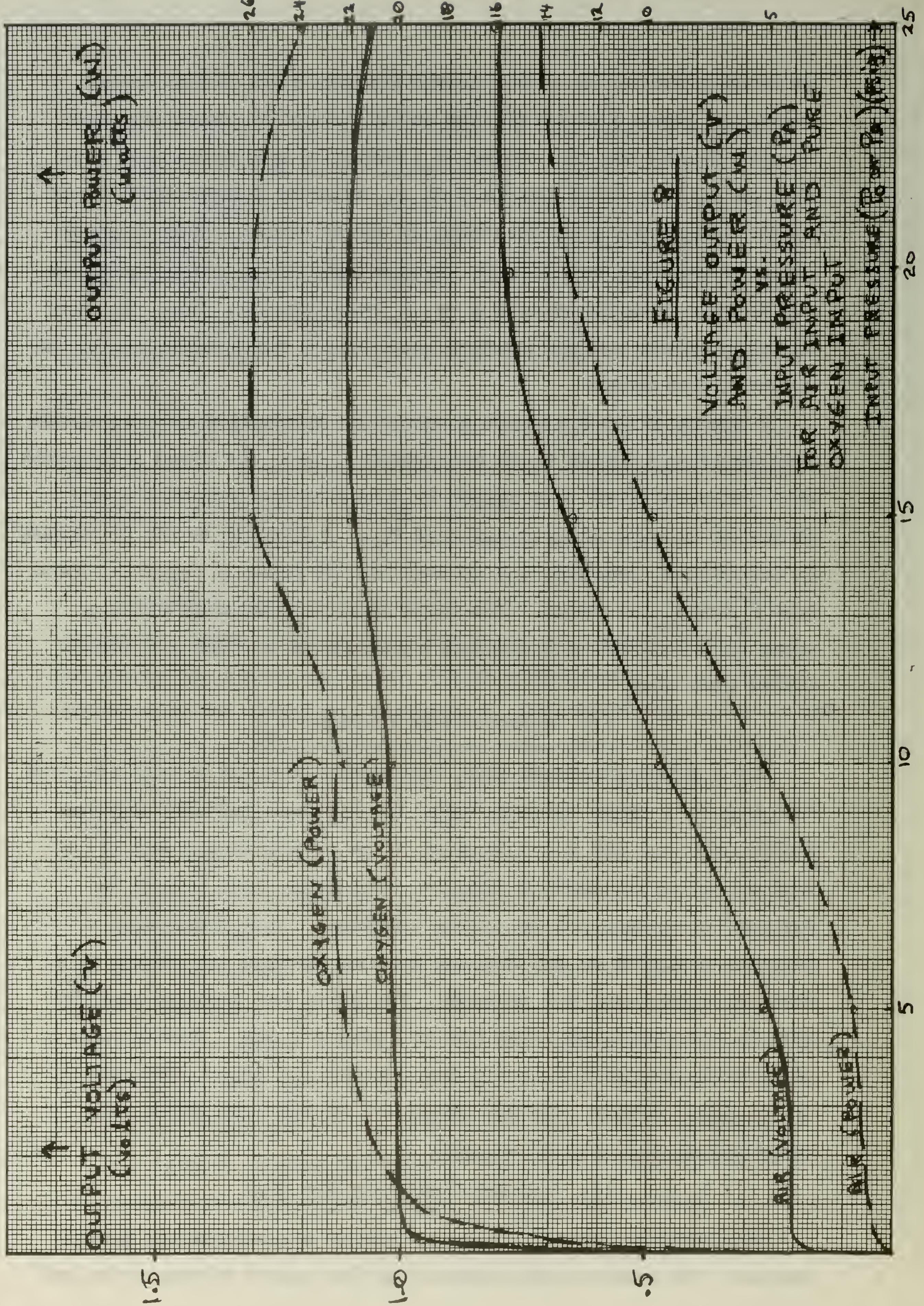


FIGURE 8
VOLTAGE OUTPUT (V) AND POWER (W) VS. INPUT PRESSURE (P_A)
FOR AIR INPUT AND PURE OXYGEN INPUT
OUTPUT VOLTAGE (V) (volts)
OUTPUT POWER (W) (watts)
INPUT PRESSURE (P_O or P_A) (psig)
OXYGEN (POWER)
OXYGEN (VOLTAGE)
AIR (VOLTAGE)
AIR (POWER)

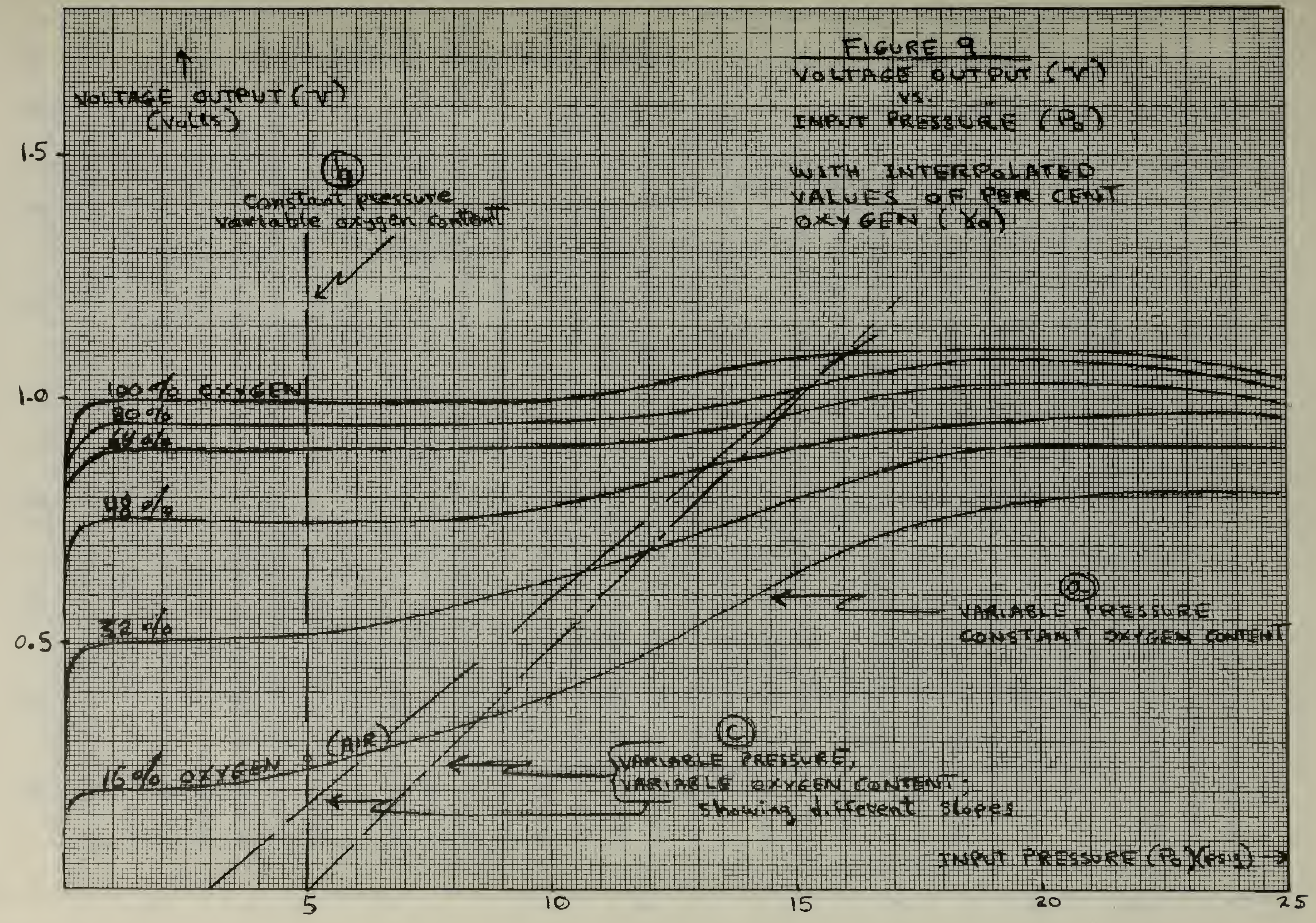


FIGURE 9
VOLTAGE OUTPUT (V)
VS.
INPUT PRESSURE (P_o)
WITH INTERPOLATED
VALUES OF PER CENT
OXYGEN (X_o)
VOLTAGE OUTPUT (V)
(Volts)
1.5
1.0
0.5
(b)
Constant pressure
variable oxygen content
100 % OXYGEN
80 %
64 %
48 %
32 %
16 % OXYGEN
(AIR)
(a)
VARIABLE PRESSURE
CONSTANT OXYGEN CONTENT
(C)
VARIABLE PRESSURE,
VARIABLE OXYGEN CONTENT;
showing different slopes
INPUT PRESSURE (P_o)(psig)
5
10
15
20
25

pressure. It would have a similar effect, providing that a sufficient flow rate was maintained to provide for removal of the water product of the chemical reaction.

12. Per Cent Hydrazine in Fuel Mixture (γ_H)

For the fuel cell used during the experiments, the maximum per cent hydrazine (γ_H) usable in the liquid fuel solution was 6 per cent. [2] The newer fuel cell used to build the Fuel Cell Research System has a newer type electrode (nickel boride) which permits use of per cent hydrazine (γ_H) as high as 15 per cent.

As the per cent hydrazine (γ_H) becomes lower, the cell output decreases and the voltage output vs. input pressure curves become more non-linear. (See Figure 6) Also, the speed of response of the system becomes slower.

For steady state output voltage conditions, the fuel cell can be considered to be just a voltage source in series with some internal resistance. [7] Though many factors combine to produce the internal resistance effect, the internal resistance (R_g) can be considered to change as a function of input air pressure (P_A) and per cent hydrazine (γ_H). Experimental results are shown in Figure 10. As γ_H decreases below one per cent, R_g rapidly approaches very large values. Notice that the lower values of R_g occur for values of P_A between 5 and 15 psig. This indicates that this region may be a good operating range for the fuel cell.

It would be difficult to use the per cent hydrazine (γ_H) as an input parameter for controlling the output voltage (V). The speed of response for such a system would be too slow. And, once in solution, it would be difficult to decrease the hydrazine content as a control measure.

There does exist, however, an optimum value of per cent hydrazine (γ_H) for the best fuel cell operation. [2] Therefore, it would be desirable to have a hydrazine sensor which, sensing a decrease in the hydrazine content of the fuel, would open a valve permitting more

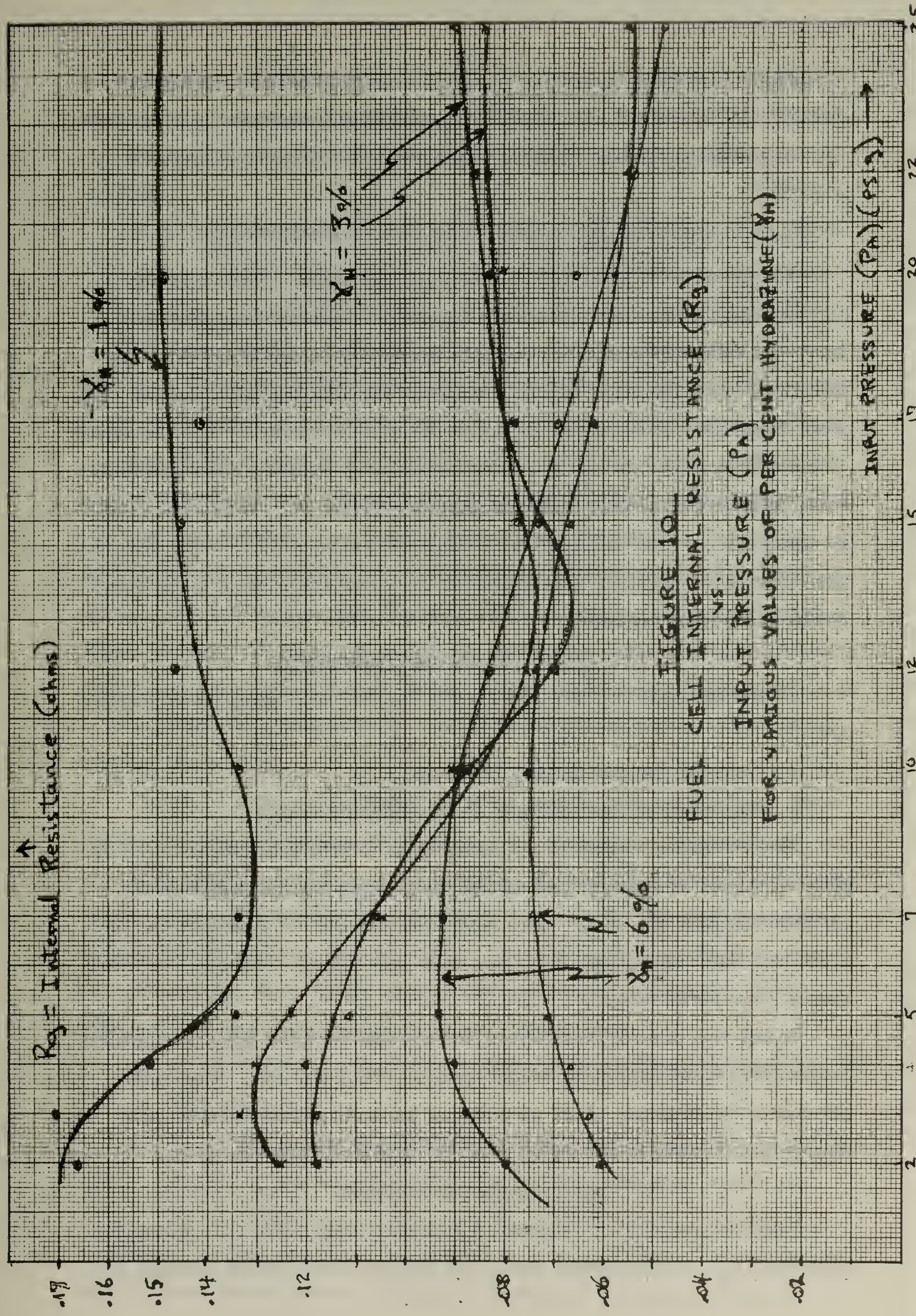


FIGURE 10
FUEL CELL INTERNAL RESISTANCE (R_g)
VS.
INPUT PRESSURE (P_A)
FOR VARIOUS VALUES OF PER CENT HYDRAZINE (γ_H)

hydrazine to enter the solution. Thus, as the hydrazine is used in the chemical reaction, it would be automatically replaced. This would be an auxilliary control system within the overall fuel cell control system.

13. Per Cent Electrolyte in Fuel Mixture (γ_E)

The potassium hydroxide electrolyte provides a liquid transport for the hydrazine. It is also capable of ion exchange and serves to carry the chemical reaction products (primarily water) away from the electrode reaction site. As this water is fed into the fuel mixture, the overall per cent electrolyte (γ_E) and per cent hydrazine (γ_H) decreases. The optimum value for γ_E is 36 per cent. [2] Values above and below this cause a decrease in the cell output voltage (V). Thus, it would also be desirable to have an auxilliary control system which would maintain the optimum electrolyte concentration. γ_E has little value as a direct control of output voltage.

14. Choice of Control Parameters

Of the methods of fuel cell control discussed, the most promising are:

1. Varying Oxygen Source Pressure
2. Varying Per Cent Oxygen in the Oxygen Source

The remaining sections are devoted to the development of a mathematical model of the fuel cell using the oxygen source pressure (P_A = air pressure) as the input. Exploration of the per cent oxygen (γ_O) as a control input parameter is proposed as the logical sequel to this series of experiments.

These two control parameters are chosen because they produce the largest and most expedient effect on the output voltage. The other parameters discussed could be used as controls, depending on the degree of complexity permitted and the sophistication desired.

15. Frequency Analysis

Approximately thirty frequency analysis tests were run, using air pressure (P_A) as the system input and the fuel cell loaded voltage (V)

as the output. The majority of the tests were run under the standard conditions described in Appendix I. Other tests were then run, changing some one condition to determine its effect on the frequency response.

A sinusoidal air pressure (P_A) input was generated using an electrical current to air pressure transducer which is shown in the diagram of Figure 3. A voltage function generator was then used to generate a sinusoidal current which caused a sinusoidal air pressure. [11] The time response of the current to pressure transducer was determined to be sufficiently more rapid than that of the fuel cell to permit assuming that it had a constant transfer function. Thus, the voltage input to the transducer was put on a trace recorder and the voltage axis of the plot was relabeled as pounds per square inch gage. The values of pressure were observed on a pressure gage and recorded on the trace. The fuel cell output voltage was also put on a trace recorder. Thus, an input (P_A) and an output (V) trace were obtained which showed phase and amplitude relationships. These were used to construct plots of output/input in decibels vs. the base ten logarithm of radian frequency (Bode Plot).

Figure 11 shows the frequency response for the fuel cell for three tests done under standard conditions for a sinusoidal peak to peak air pressure input (P_A) of 2 psig. (Curves A, B, and C) Curve D shows the response for a fuel cell under standard conditions, but with the peak to peak input pressure being 4 psig. In addition to the various chemical parameters discussed, there were two other parameters which affected the frequency response curve. They were:

1. B_p = the psig value at which the sinusoidal input pressure was biased.
2. A_p = the amplitude of the sinusoidal input pressure. i.e. $P_A = A_p \sin wt$. Note that for a 4 psig peak to peak input, $A_p = 2$ psig.

The effect of both of these parameters was mainly that of changing the amplitude of the response. Figure 7 shows the linearized fuel cell

operating regions, and it can be seen that the point of location of the input bias as well as the input amplitude would affect the amplitude swing of the output voltage.

Notice that curves A, B, and C of Figure 11 are very similar in shape, particularly in the region from one to twenty radians per second. The amplitudes of each curve vary somewhat. This can be attributed to the fact that it is very difficult to achieve exactly the same conditions for each test. The slope of the gain curve may have varied slightly between tests, thus accounting for the difference in amplitudes of the curves A, B, and C.

In the frequency region between one tenth and one radian per second, the frequency response is more irregular. The reliability of the data taken for these frequencies is not as good as that for higher frequencies. Curves A, B, and C represent the three typical shapes which were obtained in all of the tests conducted.

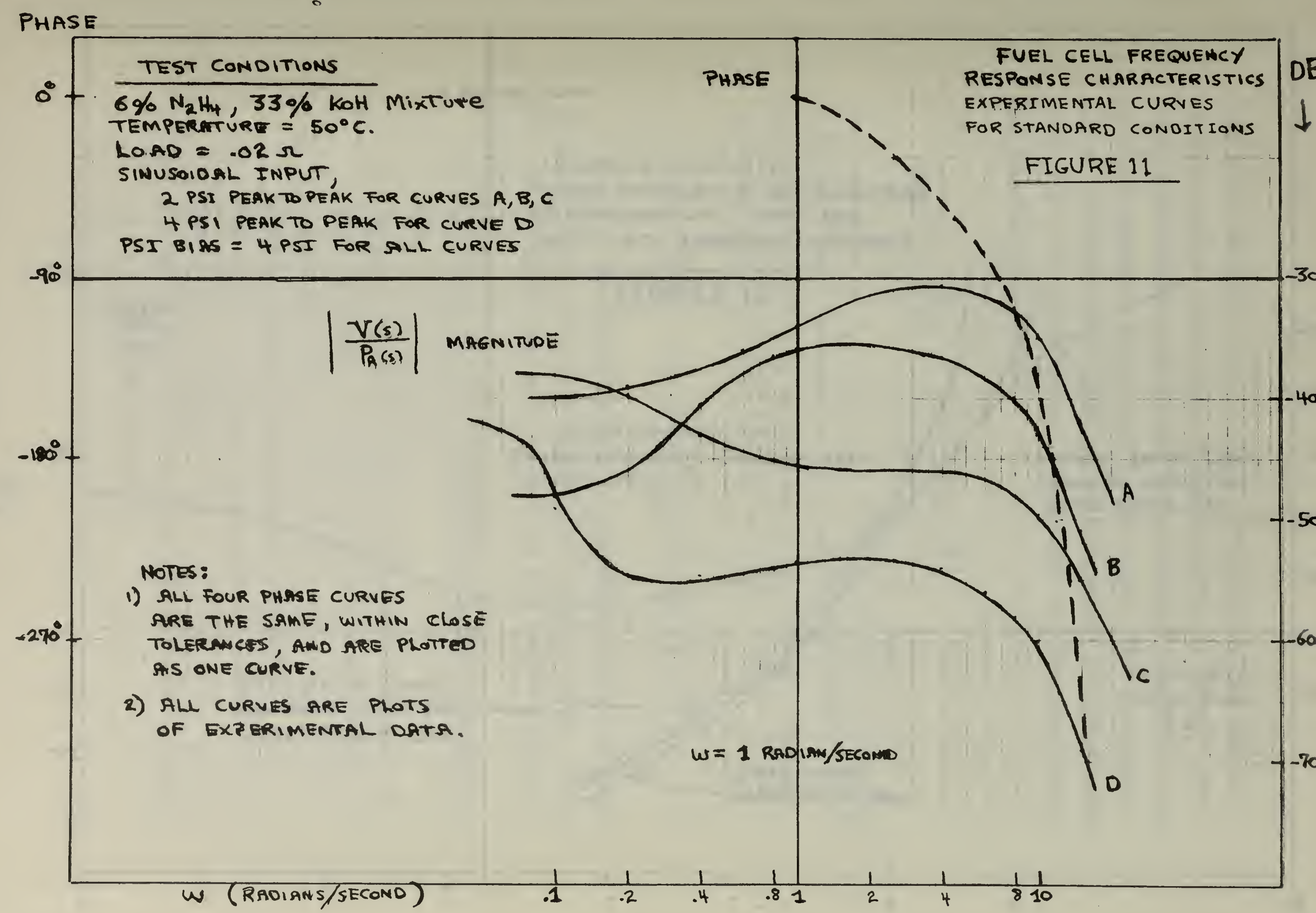
Taking an average of the frequency response curves, a fuel cell transfer function can be postulated. The frequency response curves indicate the presence of three poles in the vicinity of ten radians per second. The curves consistently showed an eighteen decibel per octave drop near this frequency. The frequency response at the lower frequencies indicates the presence of one zero and one pole. Specifically, the averaged frequency response indicates that the following transfer function is valid:

$$G_{FC}(s) = \frac{V(s)}{P_A(s)} = \frac{26(s + .3)}{(s + 1)(s + 10)^3}$$

Or, more generally:

$$G_{FC}(s) = \frac{V(s)}{P_A(s)} = \frac{K(s + z)}{(s + P_1)(s + P_2)(s + P_3)(s + P_4)}$$

Now, the phase characteristic of the frequency response must be considered. Figure 12 shows a Bode Plot for the fuel cell transfer function ($G_{FC}(s)$) derived from the averaged frequency response curves.


PHASE
TEST CONDITIONS
6% N_2H_4, 33% KoH Mixture
TEMPERATURE = 50°C.
LOAD = .02 Ω
SINUSOIDAL INPUT,
2 PSI PEAK TO PEAK FOR CURVES A, B, C
4 PSI PEAK TO PEAK FOR CURVE D
PSI BIAS = 4 PSI FOR ALL CURVES
PHASE
FUEL CELL FREQUENCY
RESPONSE CHARACTERISTICS
EXPERIMENTAL CURVES
FOR STANDARD CONDITIONS
FIGURE 11
DB
$\left|\frac{V(s)}{P_A(s)}\right|$ MAGNITUDE
0°
-90°
-180°
-270°
-30
-40
-50
-60
-70
A
B
C
D
NOTES:
1) ALL FOUR PHASE CURVES ARE THE SAME, WITHIN CLOSE TOLERANCES, AND ARE PLOTTED AS ONE CURVE.
2) ALL CURVES ARE PLOTS OF EXPERIMENTAL DATA.
w = 1 RADIAN/SECOND
w (RADIANS/SECOND)
.1
.2
.4
.8
1
2
4
8
10

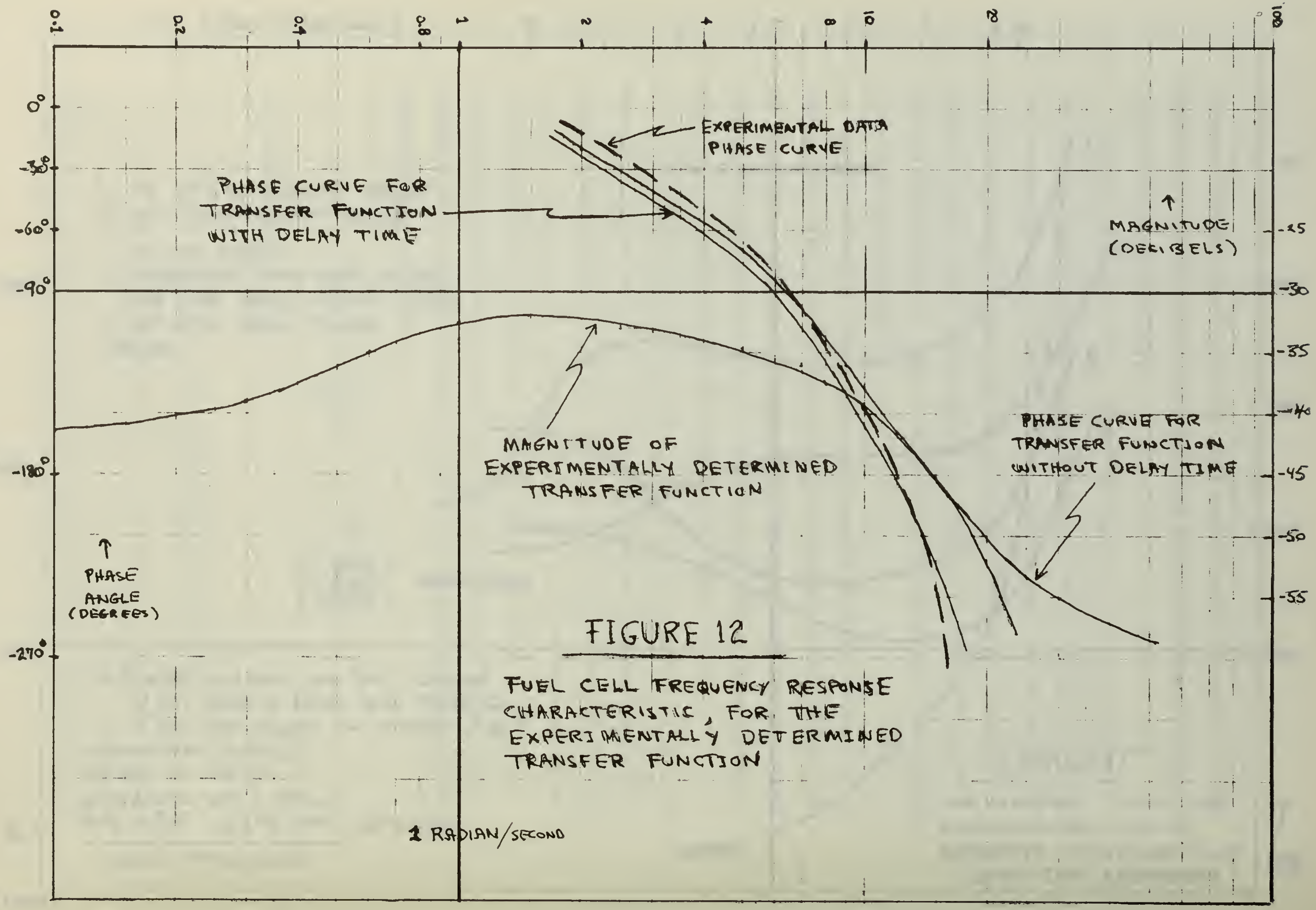


FIGURE 12

FUEL CELL FREQUENCY RESPONSE CHARACTERISTIC, FOR THE EXPERIMENTALLY DETERMINED TRANSFER FUNCTION

Notice that the phase curve for $G_{FC}(s)$ does not match the experimentally obtained phase curve. The latter decreases steeply in the vicinity of ten radians per second, while the former approaches a negative 270 degrees as should a third order system. This discrepancy can be resolved by postulating that the fuel cell has a time delay characteristic in its transfer function. This would cause the averaged fuel cell transfer function to be:

$$G_{FC}(s) = \frac{V(s)}{P_A(s)} = \frac{26(s + .3)\, e^{-.05s}}{(s + 1)(s + 10)^3}$$

The phase curve for $G_{FC}(s)$ with the time delay function is also plotted in Figure 12, as is the experimentally obtained phase curve. Comparison of these two show that they match quite closely. Therefore, the general fuel cell transfer function becomes:

$$G_{FC}(s) = \frac{V(s)}{P_A(s)} = \frac{K(s + z)\, e^{-\alpha s}}{(s + P_1)(s + P_2)(s + P_3)(s + P_4)}$$

This fuel cell transfer function is a linearized function for a system which is very non-linear over its entire operating region. Therefore, the following conditions must hold for this transfer function to be valid:

1. The operating region is always for an input air pressure between 3 psig and 15 psig.
2. K is determined by the shape of the input-output curve. It can be linearized, as shown in Figure 7, or expressed as a polynomial relation, but its values in the vicinity of the pressure operating region must be determined.
3. Step inputs or sinusoidal input amplitudes must be limited to a maximum of 4 psig.
4. The values of the poles and zeros will vary slightly depending on the operating conditions.

5. The value of α, the time delay constant, may also vary depending on operating conditions.

The values of the poles, the gain, the zero, and the time delay constant found for the averaged response will be valid for a fuel cell operating under standard conditions as defined in Appendix I.

It is emphasized that this model is valid for an air pressure (P_A) input only. The oxygen pressure (P_O) input was analyzed for steady state output purposes, but no frequency or transient response tests were made using an oxygen input. When using oxygen source pressure (P_O or P_A) as an input, P_A is much preferred from a control point of view. [3] For a pure oxygen pressure input (P_O), there is very little change of output voltage as a function of P_O.

The effect of changing the fuel cell chemical parameters from standard conditions is summarized as follows:

1. Per cent hydrazine in fuel mixture (γ_H): A decrease in γ_H causes decrease in the amplitude of the frequency response as well as a slowing of the system response. As γ_H decreases, the poles of $G_{FC}(s)$ tend to move to lower values.
2. Fuel Cell temperature (T_{FC}): Variations in temperature cause only a small variation in the amplitude of the frequency response.

These were the only parameters affecting the frequency response which were experimentally studied.

16. Transient Analysis

As a natural sequel to the frequency analysis, the response of the fuel cell to a step input was studied. The transfer function $G_{FC}(s)$ determined in Section 15 from the frequency analysis was used as a model. This model was put into a digital computer program which would solve the differential equations involved. The output of the digital computer program was then compared to an actual fuel cell step response.

In keeping with the restrictions imposed for using $G_{FC}(s)$, the fuel cell was set to operate at a steady state value corresponding to a

5 psig input. A step input from 5 to 7 psig was then applied. The output voltage response of this step input is shown in Figure 13, normalized such that the 5 psig steady state voltage is set to zero. The output of the $G_{FC}(s)$ mathematical model for a 2 psig input is also shown. The time delay of the system was ignored in constructing Figure 13. The similarity of the two responses is indicative of the validity of $G_{FC}(s)$ as a mathematical model of the fuel cell.

If a fuel cell is operating at some steady state voltage input and the input air pressure (P_A) is reduced to zero as a negative step function, the fuel cell response does not follow the $G_{FC}(s)$ mathematical model. Figure 14 shows the fuel cell output voltage after the air pressure input has been reduced from 15 to zero psig. It is characterized by the following:

1. A quick exponential decay to a voltage plateau.
2. A delay at this plateau of the order of seven seconds.
3. A long exponential decay approaching zero voltage.

Figure 14 also shows the fuel cell output voltage (V) response to a reduction of input air pressure (P_A) from 15 to 5 psig. Note that this response is what might be expected from a system with a transfer function $G_{FC}(s)$. The step from 15 to 5 psig does not violate the operating region restriction placed on $G_{FC}(s)$ as does the 15 to zero step.

The voltage plateau which follows the quick decay corresponds to the natural operating level for the fuel cell which was mentioned in Section 7. Since a significant amount of oxygen is available in the porous electrodes after the input air pressure (P_A) is reduced to zero, the normal chemical reaction is sustained for awhile, and the output voltage (V) remains approximately constant. After a delay (about seven seconds), the output voltage begins a slow decay. This is a result of the chemical reaction becoming starved for oxygen. However, as long as oxygen and hydrazine are available in the porous electrodes, some output voltage will exist.

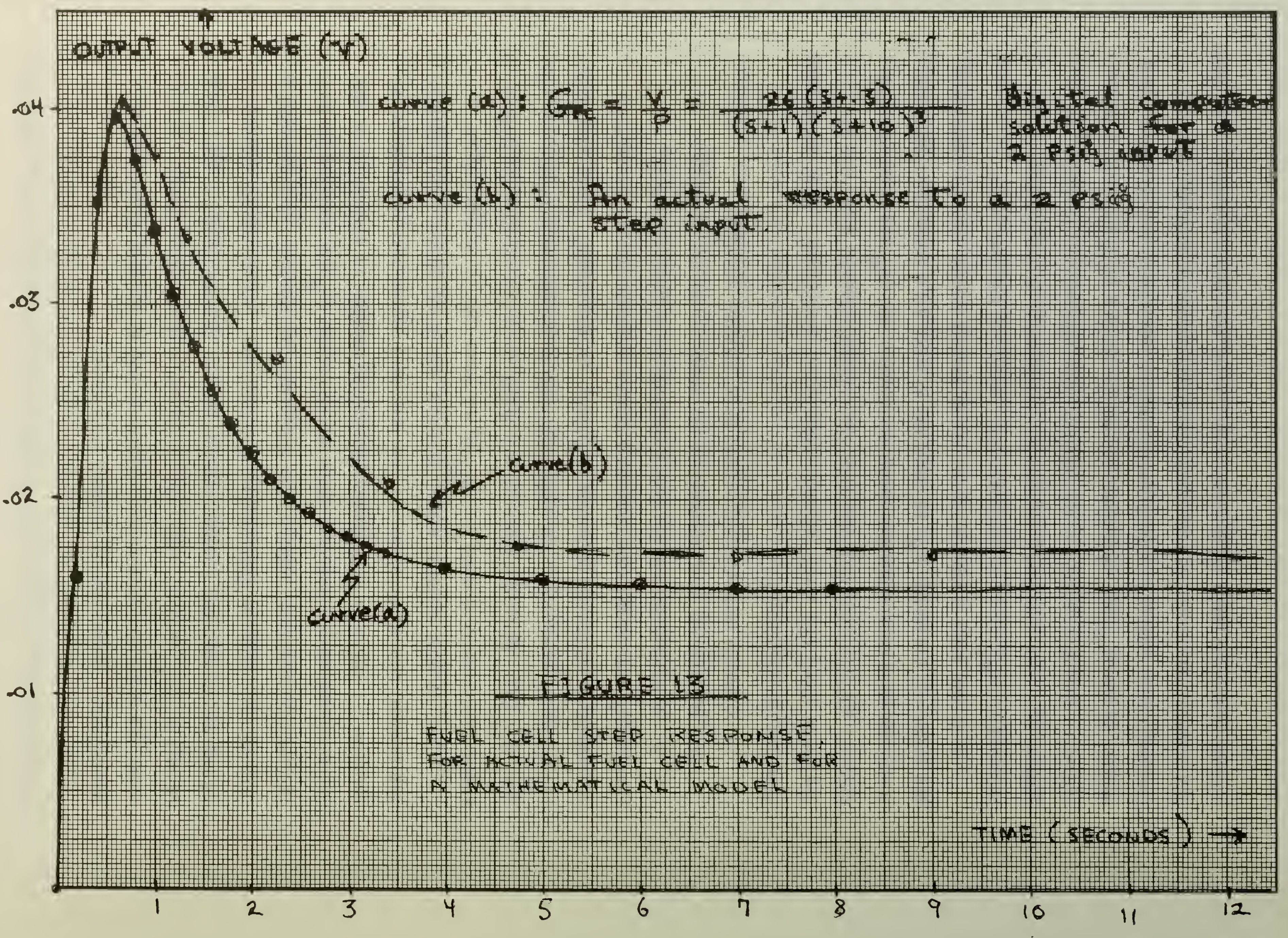


FIGURE 13

FUEL CELL STEP RESPONSE, FOR ACTUAL FUEL CELL AND FOR A MATHEMATICAL MODEL

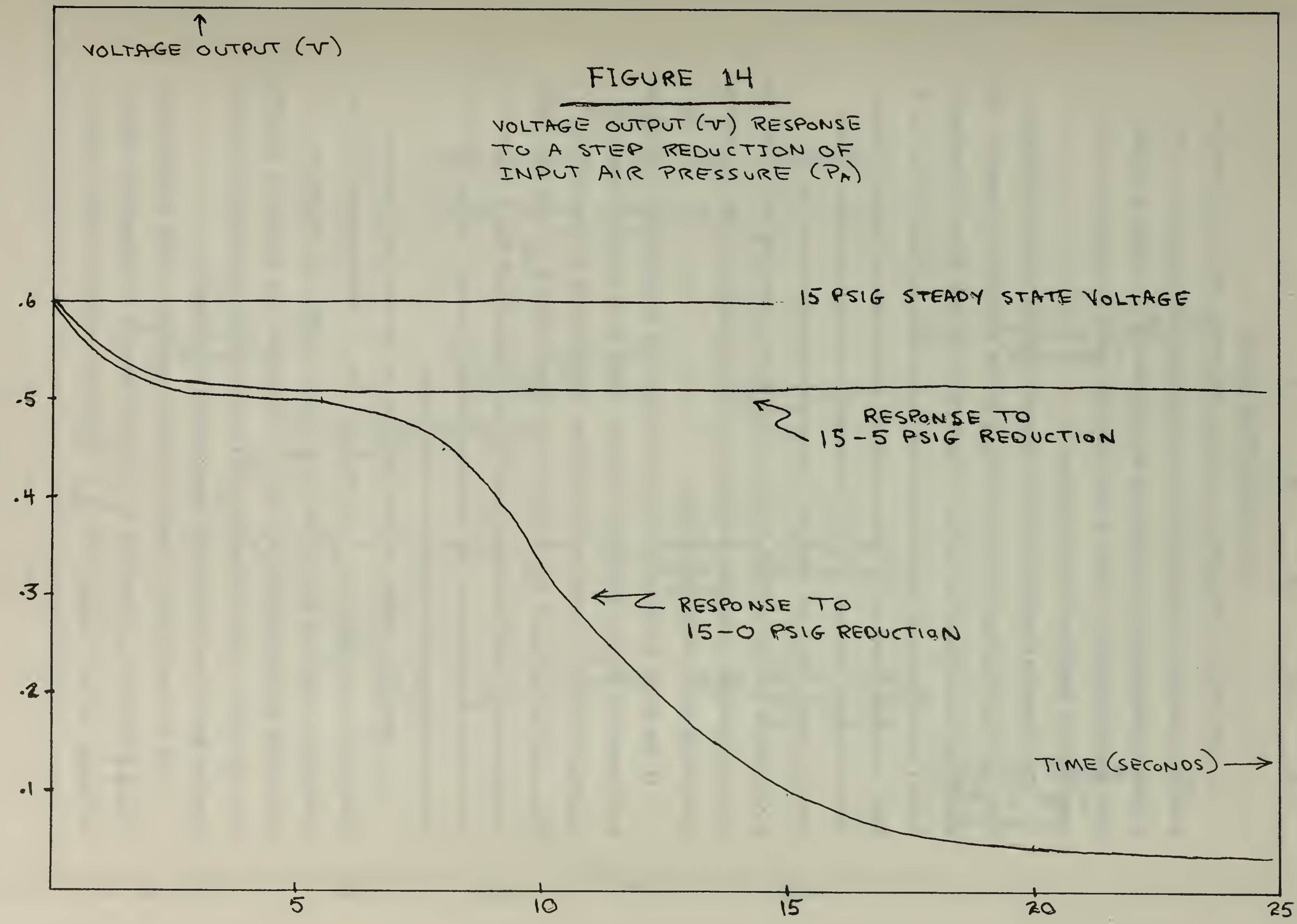


FIGURE 14

VOLTAGE OUTPUT (v) RESPONSE TO A STEP REDUCTION OF INPUT AIR PRESSURE (P_A)

17. Time Delay Effect

A time delay in the fuel cell output response was found through frequency analysis methods and was discussed in Section 15. This effect is described by multiplying $G_{FC}(s)$ by $e^{-\alpha s}$, where α is the time delay constant. Since α may vary for certain conditions, it is important to examine these changes.

The chemical saturation of the oxygen electrode with hydrazine fuel solution will cause the time delay of the system to increase. This electrode saturation may occur if the system is shut down improperly. It will occur to some degree whenever the system is shut down. [2] The time delay caused by this electrode saturation can be as high as thirty seconds or more. [3] If a feedback control system is to be used in controlling the fuel cell, such time delays would be unacceptable, as the system would be unstable. Upon start up, the fuel cell will exhibit some sluggishness, but will quickly attain its normal time delay of .2 seconds or less.

If the input air pressure (P_A) is reduced to zero and the hydrazine fuel pressure (P_H) is kept at its normal value (1-3 psig) for recirculating the fuel, the oxygen electrode will become saturated. If the input air pressure (P_A) is turned on after a time t_{po}, the fuel cell time delay (t_d) will have increased. The oxygen now has to react with the excess hydrazine at the oxygen electrode before a normal potential can be developed across the two electrodes.

An additional effect is that the poles of the fuel cell transfer function are changed as t_{po} increases. This is demonstrated by the change in overshoot of the fuel cell output voltage (V) response to a step input air pressure (P_A). As t_{po} increases, the overshoot becomes less and less, finally showing the response of an overdamped system. These effects are both shown graphically in Figure 15.

The fuel cell delay time found when operating under standard conditions (defined in Appendix I) is of the order of .2 seconds or less. With this value of delay time (t_d), a stable feedback control system

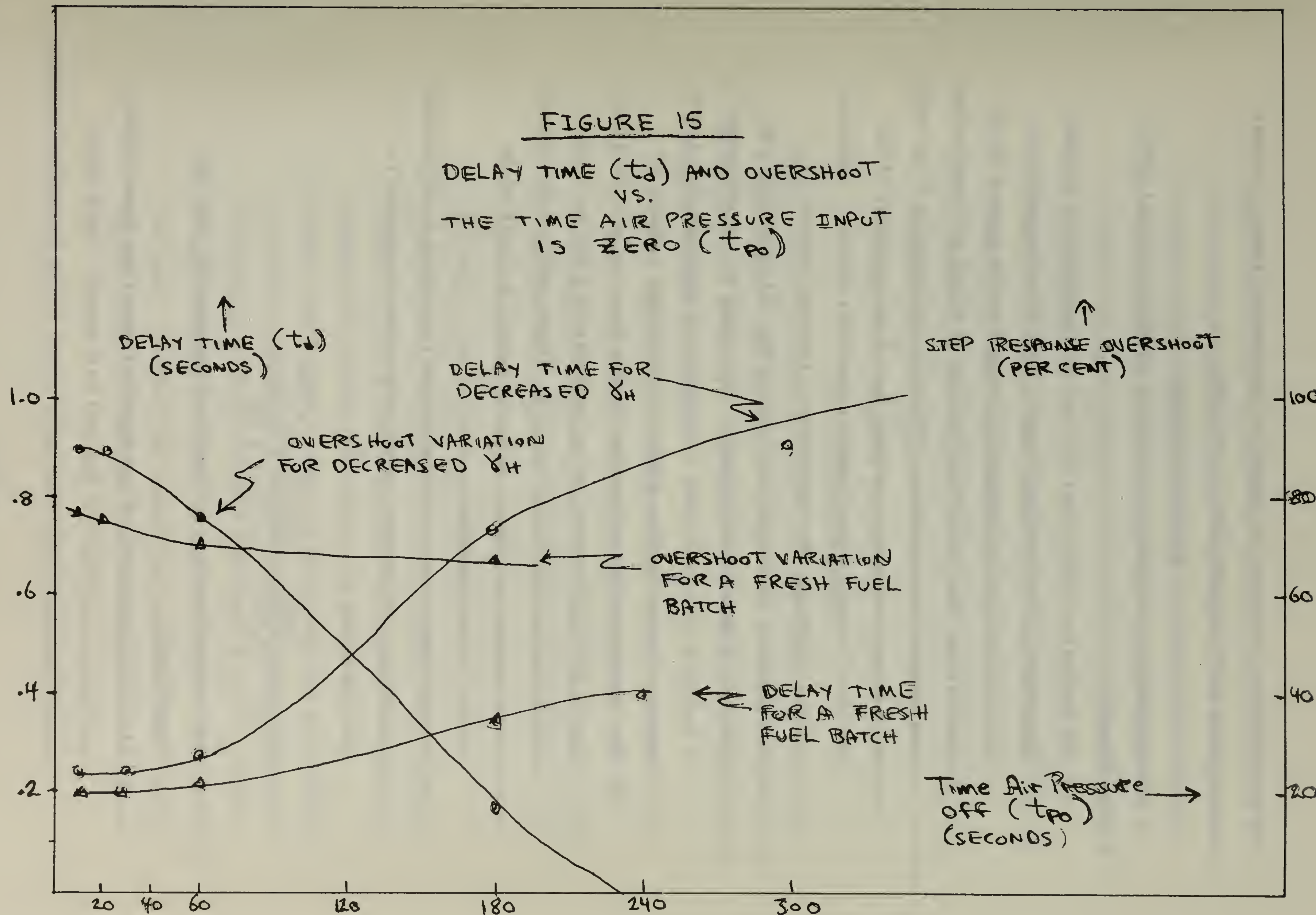


FIGURE 15
DELAY TIME (t_d) AND OVERSHOOT
VS.
THE TIME AIR PRESSURE INPUT
IS ZERO (t_{PO})
DELAY TIME (t_d)
(SECONDS)
STEP RESPONSE OVERSHOOT
(PER CENT)
DELAY TIME FOR
DECREASED γ_H
OVERSHOOT VARIATION
FOR DECREASED γ_H
OVERSHOOT VARIATION
FOR A FRESH FUEL
BATCH
DELAY TIME
FOR A FRESH
FUEL BATCH
Time Air Pressure
off (t_{PO})
(SECONDS)
1.0
.8
.6
.4
.2
100
80
60
40
20
20
40
60
120
180
240
300

can be designed. However, it should be designed to keep t_{po} equal to zero, or at most not more than 20 seconds.

18. Conclusions

The conclusions reached as a result of the work outlined herein are as follows:

1. The hydrazine oxygen fuel cell can be controlled by varying parameters of the chemical inputs. The effectiveness and desirability of so controlling a fuel cell would depend on the application. The "long time" control of a fuel cell may be the most desirable application. The transient response to an input such as air pressure is not fast, nor is the accuracy of the predicted response good over all operating regions. However, control of the per cent hydrazine in the fuel solution (γ_H) would permit the fuel cell output voltage (V) to be kept constant for a long period of time. This could be supplemented by a feedback control system which used air pressure (P_A) as an input and permitted fine control of the output voltage (V).
2. The parameters of the chemical inputs found to be most effective in fuel cell control are air pressure (P_A) and per cent oxygen in the oxygen source (γ_o). These produce the largest output change for a given range of inputs, as well as the fastest system response.
3. A mathematical model for the fuel cell operating under standard conditions, and subject to the restrictions discussed in Section 15 is:

$$G_{FC}(s) = \frac{V(s)}{P_A(s)} = \frac{26(s + .3)e^{-.05s}}{(s + 1)(s + 10)^3}$$

   The transfer function for the input parameter γ_o was not determined.
4. All of the parameters of the chemical inputs are inter-related and have some effect on the fuel cell output. Their inter-relationship and effect has been shown in the preceeding sections.

Any number of these parameters could be used to control a fuel cell depending on the effect desired, the degree of complexity permitted, and the degree of sophistication sought.

5. The fuel cell is a non-linear device. It can be modeled by defining operating regions and linearizing the characteristics therein.
6. The fuel cell has a time delay in its response which can become significant under certain conditions.
7. A feedback control system for the fuel cell is feasible. The transfer function $G_{FC}(s)$ obtained through experimental methods is adequate for studying the problem of fuel cell control.

19. Recommendations

The "Fuel Cell Research System" was designed and constructed as a teaching aid, but also for the purpose of providing the means for further fuel cell research. Therefore, the following recommendations for future projects are listed.

1. Verify the graphical data presented herein. As previously noted, the fuel cell used for these experiments was not operating at full power, and it eventually developed a leak. Also, the fuel cell in the "Fuel Cell Research System" is a newer Model 100H which has different electrodes than did the model used in these experiments.
2. Experimentally examine the per cent oxygen in the oxygen source (γ_o) as a control parameter. Determine a transfer function for the fuel cell with γ_o as an input.
3. Drive a small, low voltage DC motor with the fuel cell and use motor velocity as a system output. Derive a transfer function for a velocity output and either a P_A or γ_o input.
4. Design a feedback control system for the fuel cell and close the loop. Compare the closed loop response with that predicted using the experimentally derived transfer functions.

5. Examine in more detail the inter-relationship of the parameters of the chemical inputs and the fuel cell operating regions. Develop a flow graph which will show the effect of each parameter on the fuel cell output amplitude and speed of response.
6. Examine "long time" fuel cell control by noting the change of some control parameter required to maintain a constant voltage as the hydrazine fuel is depleted. Either air pressure (P_A) or the per cent oxygen in the oxygen source (γ_O) could be used as the input control parameter.

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APPENDIX I

EXPERIMENTAL PROCEDURE FOR A COMPREHENSIVE TEST OF THE FUEL CELL SYSTEM

IA. Standard Conditions:

For a system with many variables, in order for the effect of each to be studied, a standard condition must be established. Then, one variable at a time may be permitted to change. The following is defined as the "Standard Condition" for the fuel cell for the experiments described.

γ_H = per cent hydrazine in the fuel solution = 6%

γ_E = per cent potassium hydroxide in the fuel solution = 33%

T_{FC} = operating temperature = $50^{\circ}C$.

B_p = input pressure bias = 4 psig

A_p = input pressure sinusoidal amplitude for frequency analysis (one half the peak to peak value) = 1 psig

R_L = fuel cell load = approximately .02 ohms. (This value was approximated by using an ammeter only as the load.)

Note: A new "Standard Condition" will have to be established for the "Fuel Cell Research System". More parameters are measurable, and the optimum γ_H is 10 per cent, where for the first cell, the optimum γ_H was 6 per cent.

IB. Comprehensive Test:

The following procedure was found to provide sufficient data to adequately examine the parameters of the fuel cell:

1. Record any deviations from the "Standard Conditions" desired for the experiment.
2. Record time of starting the experiment.
3. Record input psig (P_A or P_O) for 1-25 psig vs. the following: open circuit voltage (E), loaded output voltage (V) and current (I). From this data, calculate fuel cell internal resistance (R_g), load resistance (R_L), and fuel cell power output (W).

4. Record traces of output voltages for step inputs in the operating region of concern. These step inputs should be near the value of B_p to be used in the frequency analysis.
5. Record a step input and the output response, noting the time delay (t_d). Turn off the input air pressure, vary t_{po} from zero to 300 seconds in 60 second intervals. Note the effect on t_d. Be careful not to cause cell reversal.
6. Record the magnitude and phase of the output/input ratio while varying the frequency of the input pressure (P_A) sinusoid from .01 cps to 3 cps. Make sure that the input pressure magnitude (A_p) remains constant. Calculate the magnitude in decibels and the frequency in radians per second. Construct a Bode Plot.
7. Repeat steps three through six, noting that these were done at the end of the experiment. Note any changes caused by the reduction of γ_H which occurs as the hydrazine is used up.
8. Record the time of completing the experiment. Number the experiment for future reference.

Note: The average time to conduct one comprehensive test was two hours. This test is designed to study the P_A parameter primarily. Modifications to this general format will be required to study another parameter such as γ_o.

APPENDIX II

DESCRIPTION OF HYDRAZINE-OXYGEN FUEL CELL RESEARCH SYSTEM

IIA. General Description:

The Fuel Cell Research System is pictured in Figure II-1. It consists of a stainless steel stand on rollers with shelves for the fuel cell equipment (top shelf), test equipment (middle shelf), and chemical and tool storage (bottom shelf). It has an electrical inlet which should be plugged into a 115 volt, 60 cycle source. This power is supplied to the fuel cell fuel pump and fuel tank heaters, as well as to outlet panels provided on the center shelf for test equipment. The entire structure is either stainless steel or fiberglass material which will resist the corrosive effect of the chemicals used in the fuel cell. A back panel mounts pressure and flow gages. A front panel mounts the fuel cell output jacks, electrical meters and switches.

Since the Allis-Chalmers Model 100H fuel cell is a small research model, it requires auxilliary power to run its pump and heaters. Larger models would provide this power from the fuel cell output.

The Fuel Cell Research System was designed and constructed in order to provide a platform for fuel cell research. As such, it is intended to be a flexible design, with room for additional equipment and any desired changes in circuitry. With this fact in mind, the remainder of this Appendix is presented as Figures showing the circuitry of the various systems. Changes to this circuitry should be noted, and up to date diagrams maintained in the Fuel Cell Operation Log, which is described in Appendix III. The components of the system are labeled on the stand. The circuitry should be traced and thoroughly understood before operating the system. Any component changes should be clearly relabeled.

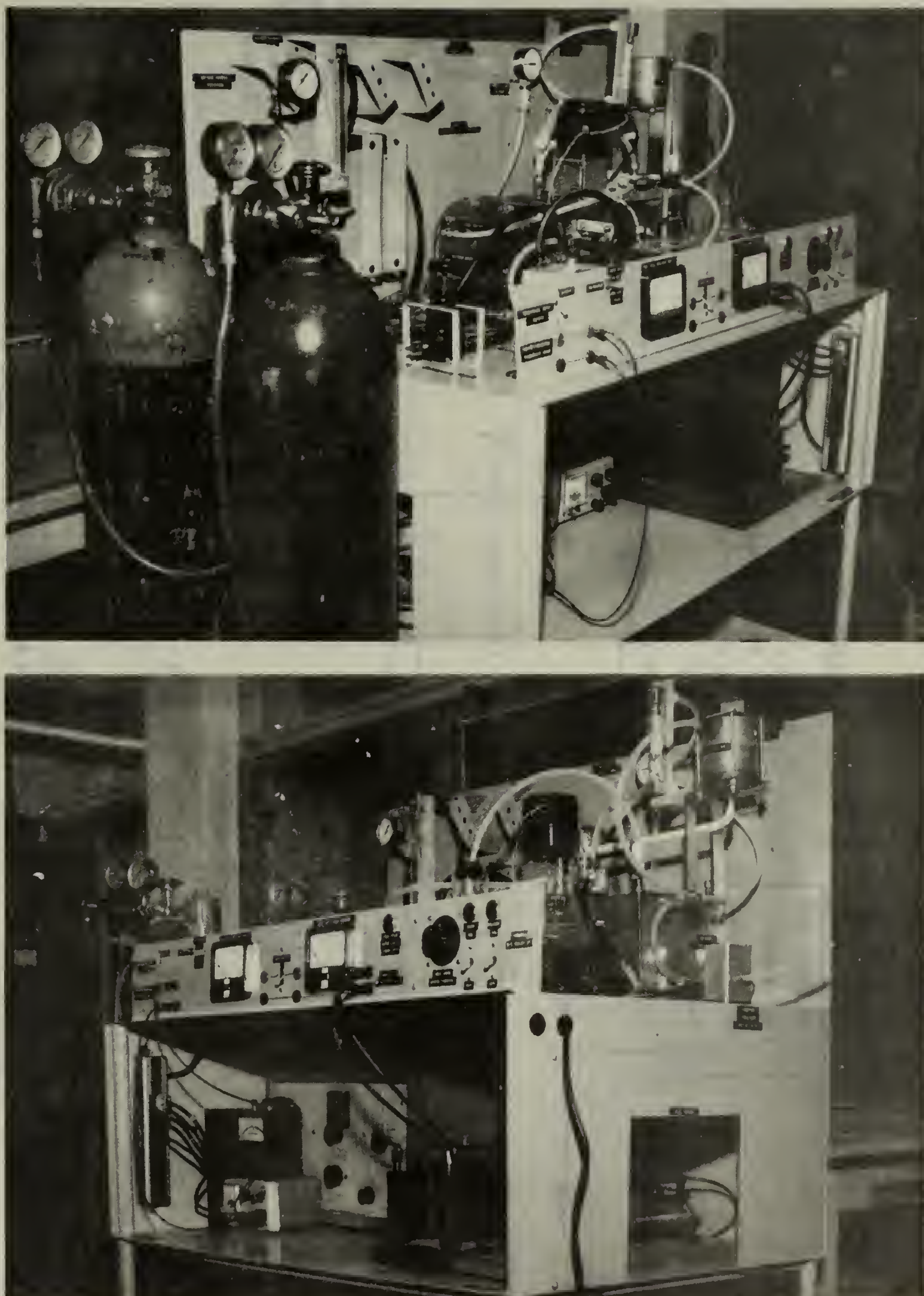


FIGURE II-1

FUEL CELL RESEARCH SYSTEM

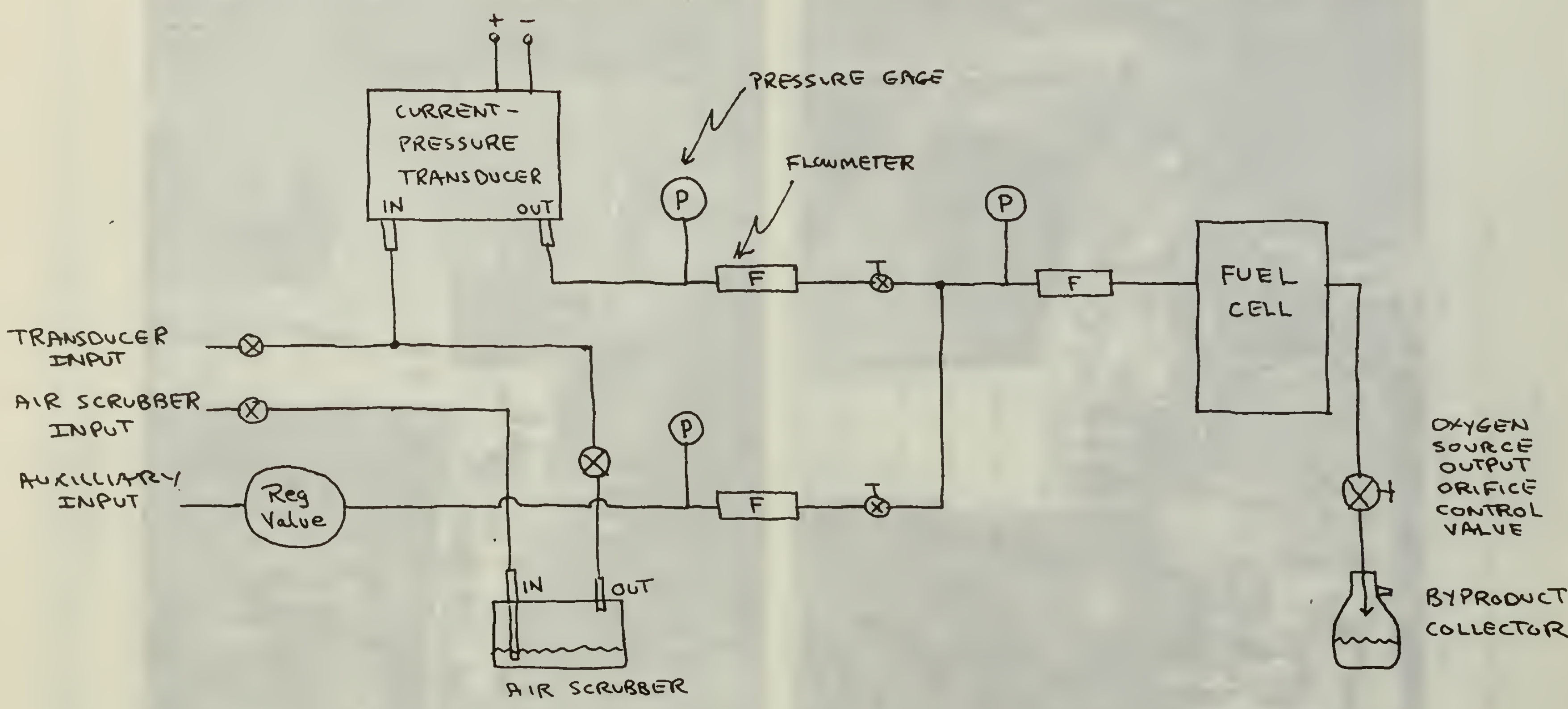


FIGURE II-2

PNUEMATIC (GAS) CIRCUITRY

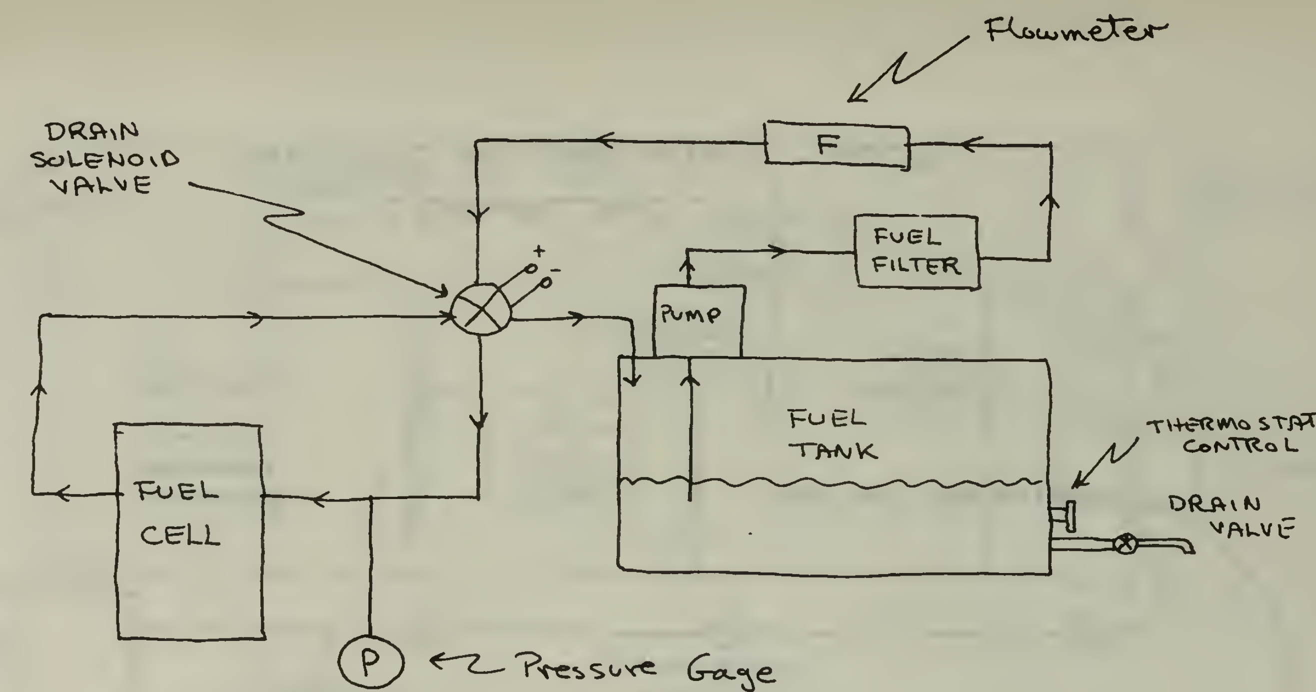


FIGURE II-3

LIQUID FUEL CIRCUITRY

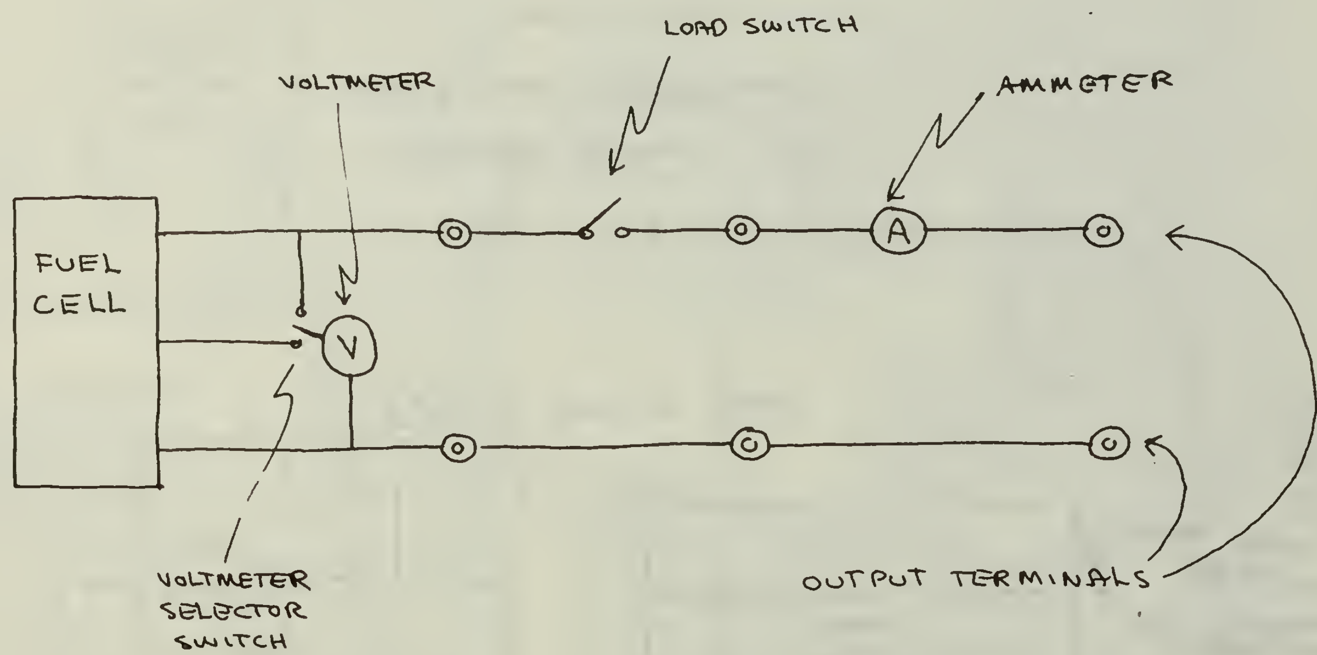
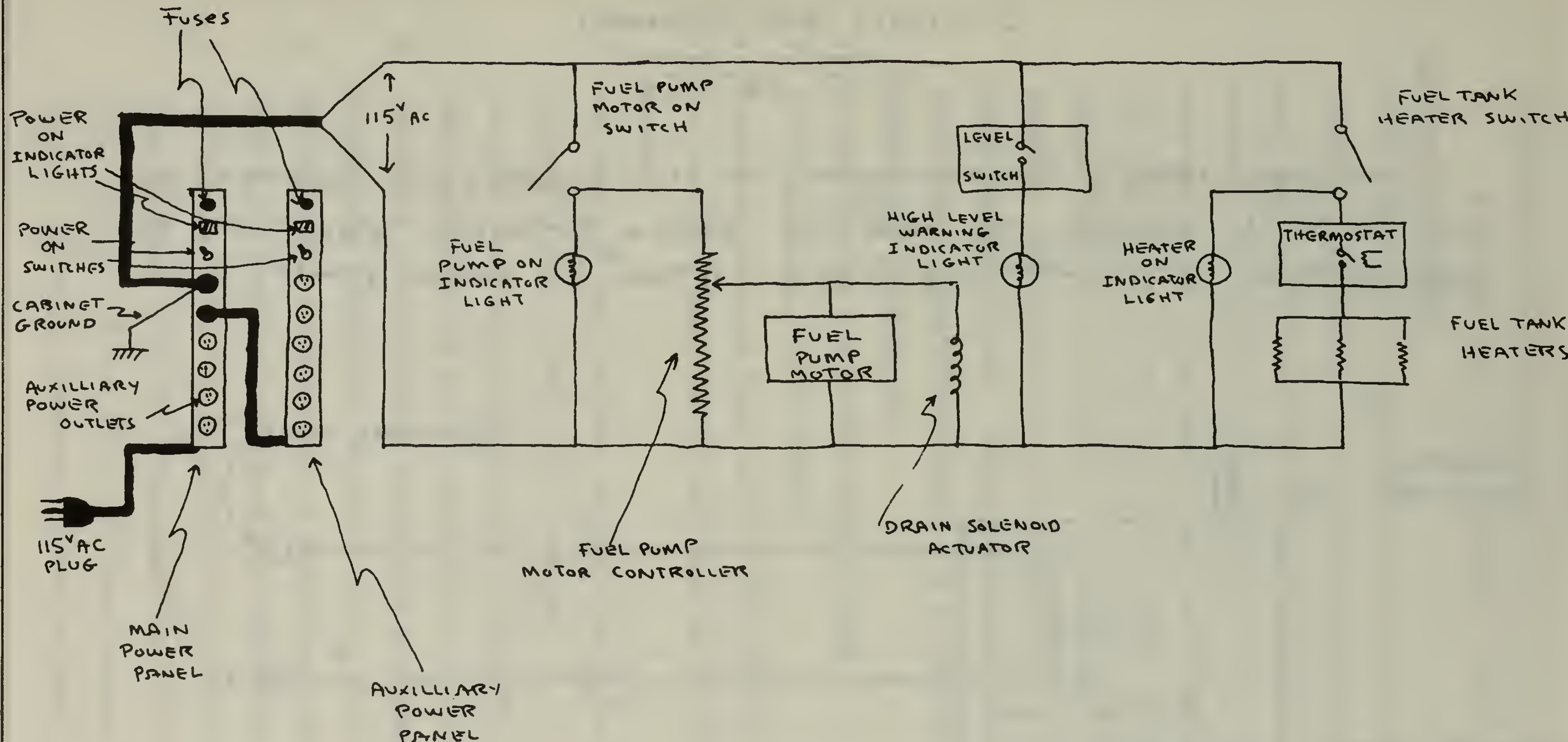


FIGURE II-4

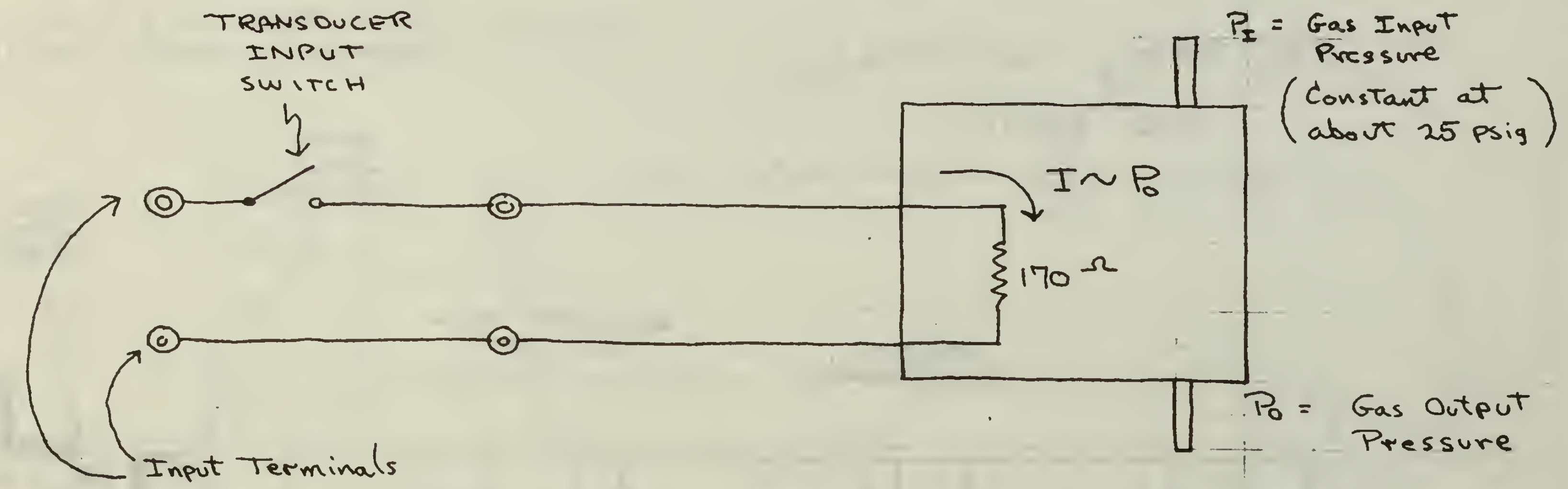
FUEL CELL VOLTAGE OUTPUT CIRCUIT



NOTE: THE SYSTEM IS GROUNDED TO THE STAINLESS STEEL STAND MOUNTING THE FUEL CELL EQUIPMENT

FIGURE II-5

AUXILLIARY POWER CIRCUIT



A current range of zero to fifty miliamperes is proportional to an output pressure range of zero to twenty-five pounds per square inch (gage), in an approximately linear fashion.

FIGURE II-6

TRANSDUCER CIRCUIT

APPENDIX III

OPERATING INSTRUCTIONS AND SAFETY PRECAUTIONS

FOR THE FUEL CELL RESEARCH SYSTEM

IIIA. Light-off Procedure:

1. Be familiar with all system circuitry, operating procedures and the instruction manual. [2] Read the last entry in the Operation Log and determine the status of the fuel batch and whether or not proper maintenance has been carried out. Locate the system in an open or well ventilated space. STANDARD ELECTRICAL SAFETY PRECAUTIONS PROMULGATED BY THE DEPARTMENT OF ELECTRICAL ENGINEERING SHOULD BE OBSERVED. SEE SECTION D OF APPENDIX III FOR CHEMICAL SAFETY PRECAUTIONS. WARNINGS CONCERNING CARE IN HANDLING COMPRESSED GASES ARE CONTAINED IN THE OPERATING PROCEDURE.
2. Locate required gas bottles next to stand.
3. Put wheel brakes on the stand.
4. Put all switches on front panel in OFF position.
5. Put auxilliary panel switch and main power switch in OFF position.
6. See that fuel tank scrubber bottle is about one third full of a dilute solution of acetic acid (vinegar).
7. See that the oxygen source output by-product collector is about one third full of a dilute solution of acetic acid.
8. See that a bottle of dilute acetic acid solution (vinegar) is available to neutralize any KOH or N_2H_4 spills.
9. See that rags, paper towels, a screwdriver and an adjustable wrench are available to correct any leak which could develop.
10. See that the table is clear of all unnecessary equipment.
11. If air scrubber is to be used, determine if it contains any 45% KOH solution. If not, fill to no more than one inch from the bottom. If the solution has not been replaced for the past

ten hours of operation, replace it. [12]

12. See that all valves are placed in the CLOSED or OFF position.
13. Set the voltmeter selector switch to the middle OFF position and zeroize the voltmeter and the ammeter.
14. Trace the liquid fuel and the pneumatic systems, insuring that no hoses have become loose. The electrical systems should be traced periodically.
15. Connect the gas bottle hose to the desired input. CAUTION. HANDLE COMPRESSED GAS WITH CARE.
16. Arrange the test equipment required on the middle shelf, plug it into the auxilliary power panel, and make necessary wiring to the front panel.
17. Make the required fuel cell load connections to the fuel cell output terminals.
18. Check the level indicator on the fuel tank. Look at the Operation Log, determine whether or not a fuel batch is in the fuel tank. If so, determine its age and whether or not to replace the fuel batch.
19. If the fuel batch requires only the addition of more hydrazine, unscrew the filling plug and insert a glass or stainless steel funnel. Measure the required amount of hydrazine solution and pour it carefully into the funnel. DANGER. HANDLE HYDRAZINE CAREFULLY. Replace the filling plug.
20. If the fuel batch requires total replacement, mix a new fuel batch. Obtain a beaker for collecting the old batch. Remove the nozzle from the drain valve outlet and remove the drain valve guard. Replace the drain nozzle. Place the beaker under the nozzle, crack the drain valve and drain the fuel tank. DANGER. HANDLE FUEL SOLUTION CAREFULLY. <u>Neutralize the old fuel batch with dilute acetic acid before disposing of it</u>. Close the drain valve, replace drain valve guard and drain nozzle. Put glass or stainless steel funnel

into filling plug. Carefully pour in the new fuel batch. Two liters is the minimum necessary for proper pump suction. Remove the funnel and replace the fill plug. Make sure the fill plug is still connected to the tube leading to the fuel tank scrubber.

YOU ARE NOW READY TO BEGIN THE EXPERIMENT

21. Plug in the system to a 115 volt, 60 cycle source. Turn on the main power switch (middle shelf, right hand side) and the auxillary panel switch (middle shelf, left hand side). Observe red indicator lights on the outlet panels.

22. Set up valves as necessary to provide the gas input desired. Activate the transducer control circuit if it is to be used. Make sure you know where your prime method of gas pressure control is.

23. Make sure the gas tank regulator valve is backed out. Crack the main valve on the gas tank, observing the tank pressure. Screw down on the regulator, adjusting for about 25 psig to the Research System Input.

24. Open the oxygen source output valve all the way. Adjust the main pressure control to permit gas to flow through the fuel cell. Observe residual moisture being purged from the cell. As soon as most moisture is removed, adjust the oxygen source output valve to an output orifice which will give the desired flow rate. A reading of 4-6 on the flow meter should be obtained for a gas pressure of 2 psig. See the Instruction Manual. [2]

25. Turn the motor controller to full voltage (full clockwise). Put the pump motor switch to the ON position. Observe motor shaft turn. Note the fuel pressure and flow rate. The pressure must not go over 5 psig. The flow rate should attain a reading of at least 6 on the flowmeter. If these conditions are not satisfied, turn off the motor and consult

the Instruction Manual. LEAKS ARE DANGEROUS. IF LEAKING, TURN OFF MAIN POWER AND REPAIR. After turn on, the motor controller can be adjusted to change the flow rate.

26. Turn the fuel tank heater switch to the ON position. Adjust the thermostat to provide the desired heating. BE CAREFUL NOT TO BACK THE KNOB OUT TOO FAR. [2]

27. The fuel cell should now have an output. Turn the voltmeter selector to read the voltage across one set of cell pairs, then both cell pairs.

28. Proceed with the experiment. FOR ANY EMERGENCY, THREE STEPS ARE REQUIRED TO KILL ALL POWER.

    1) MAIN POWER SWITCH OFF.
    2) GAS TANK MAIN VALVE CLOSED.
    3) FUEL CELL LOAD SWITCH OFF.

IIIB. Shut-Down Procedure:

1. Remove the load from the fuel cell by turning the load switch to the OFF position, or by removing the load leads from the fuel cell output terminals. CAUTION. If the fuel cell is operating at high power, the load switch should be used to prevent arcing.
2. Turn the fuel pump motor switch to the OFF position. Put motor control variac to full voltage postion. Observe the fuel pressure and flow rate gages. The drain solenoid valve on the top of the fuel tank should open, permitting the liquid on both sides of the fuel cell to drain into the fuel tank. This can be observed as some flow can be seen in the nylon tubes after the fuel pump is turned off.
3. Turn the fuel tank heater switch to the OFF position. Turn the thermostat to the COOL end of its range. (Clockwise)
4. Open the oxygen source outlet orifice valve, permitting an increased gas flow rate to purge moisture from the fuel cell. Continue this for approximately two minutes.
5. Turn the main valve on the gas tank to the CLOSE position. Back out the regulator valve on the gas tank. The oxygen source pressure and flow-rate should go to zero.
6. Turn OFF the auxilliary panel power switch.
7. Turn OFF the main power (115 volt) switch.
8. Unplug the Fuel Cell Research System from the 115 volt supply.
9. Disconnect the compressed gas input from the system. CAUTION. HANDLE COMPRESSED GAS WITH CARE.
10. CLOSE the oxygen source output orifice valve.
11. Place all valves in the pneumatic (gas) circuitry in the OFF or CLOSE position.
12. Turn the transducer input switch to the OFF position.
13. The voltmeter will continue to show a voltage. This is normal, as chemical reaction will result from oxygen and hydrazine

remaining in the porous electrodes. Turn the voltmeter selector switch to the OFF position.

14. Remove and store any test equipment not intended for use in the near future.
15. All valves should now be in the OFF or CLOSED position. All switches on the front panel should be in the OFF position. Check this.
16. Examine the entire cart for leaks of the liquid circuitry. If evidence of a leak is found, initiate steps immediately to fix it. Neutralize any spillage by wiping with a cloth or paper towel wetted with dilute acetic acid. DANGER. KOH and N_2H_4 LEAKS CAN CAUSE SERIOUS SKIN BURNS AND CORROSION OF PAINT AND EQUIPMENT.
17. FILL IN ALL NECESSARY DATA IN THE OPERATION LOG. THIS IS ESSENTIAL FOR MAINTENANCE AND FOR DETERMINING THE AGE OF THE FUEL BATCH IN THE FUEL TANK.
18. IF SYSTEM IS NOT TO BE USED OR RUN FOR MAINTENANCE PURPOSES WITHIN THE NEXT TWO WEEKS, CARRY OUT PROCEDURE FOR STORAGE SHUT-DOWN. [2]
19. Check to see that the stand is free from all lines. Remove wheel brake. Return stand to storage position in an OPEN OR WELL VENTILATED SPACE. Reapply wheel brake.
20. Insure that the tops of all chemical storage bottles are tightly closed.

IIIC. Storage Procedure:

1. This procedure should be followed whenever the Fuel Cell Research System is not to be used and maintenance runs cannot be held. Maintenance runs should be about 10-15 minutes twice a week. At a maximum, if a maintenance run cannot be held for 2 weeks, this procedure should be carried out.
2. Carry out the normal shut-down procedure. After step (15) of the shut-down procedure, carry out the following.
3. Remove the fuel tank drain nozzle and remove the drain valve guard. Replace the nozzle. Place a collection beaker under the nozzle and empty the fuel tank. NEUTRALIZE THE FUEL TANK CONTENTS WITH DILUTE ACETIC ACID BEFORE DISPOSING OF IT. Close the drain valve.
4. All of the liquid in the fuel tank cannot be removed without tilting the tank. CAUTION. THIS TAKES TWO PEOPLE. THE FUEL SOLUTION CAN CAUSE DANGEROUS BURNS. Remove the bolts which hold the tank to the table. Place a collection beaker under the nozzle. Crack the drain valve. Lift the inboard end of the tank, taking care not to foul any tubes. Drain all liquid from the fuel tank. Close drain valve. Rebolt tank to the table. Remove nozzle spout. Replace drain valve guard. Replace nozzle spout. Check all tube connections for tightness.
5. Remove filling inlet plug. Fill fuel tank with six liters of distilled water. Replace filling inlet plug.
6. Set up pneumatic circuitry to provide the fuel cell with a nitrogen gas input.
7. Turn main power switch to ON position.
8. Admit nitrogen gas to the fuel cell, at 2 psig, flow meter reading of 8.
9. Turn the fuel pump motor controller to full voltage position.

10. Turn the fuel pump motor to the ON position. Observe liquid pressure of 1-3 psig and flow rate meter reading of at least 6.
11. Run the system in this condition for about 10 minutes. Check the fuel cell output voltage. It should fall to zero indicating complete usage of all hydrazine and oxygen in the porous electrodes. The system should be run for about 5 minutes after the output voltage is observed to be zero.
12. Turn the fuel pump motor switch to the OFF position.
13. Turn the main power switch to the OFF position and unplug the system from the 115 volt supply.
14. Turn the main valve of the nitrogen gas tank to CLOSE position, back off the regulator, and put all pneumatic circuitry valves in the CLOSE or OFF position. Close the oxygen source output orifice valve.
15. Repeat steps (3) and (4), emptying fuel tank of all liquid.
16. Carefully disconnect all liquid and gas inputs to the fuel cell. CAUTION. SOME CAUSTIC MATERIAL MAY REMAIN. WIPE UP ALL SPILLS WITH RAG WETTED WITH DILUTE ACETIC ACID.
17. Insure that the fuel cell electrical output terminals have no load across them.
18. Securely cap all fuel cell openings to prevent drying out.
19. Neutralize the contents of the air scrubber, the fuel tank exhaust scrubber, and the oxygen source output byproduct collector with dilute acetic acid. Remove the air scrubber and the two bottles, dispose of their contents, rinse with distilled water, and replace on the stand.
20. Carry out steps (16), (17), (19) and (20) of the normal shut-down procedure.

<u>To Reactivate the System</u>:

1. Reconnect all of the inputs to the fuel cell.

2. Check all tubes and fittings for tightness.
3. Refill the fuel tank exhaust scrubber and the byproduct collector with dilute acetic acid. (About 5 per cent) Fill the air scrubber to one inch depth with 45 per cent KOH.
4. Carry out normal light-off procedure. BE WARY OF LEAKS WHEN REACTIVATING.

IIID. Chemical Mixing Instructions and Safety Precautions:

Care should be taken to avoid skin contact with any fuel cell chemicals. A standard fuel mixture of 10 per cent hydrazine and 33 per cent potassium hydroxide (10-33 Mixture) can be obtained as follows: Into a one liter container, measure 160 ml (mililiters) of 64 per cent hydrazine solution, 740 ml of 45 per cent potassium hydroxide solution, and 100 ml of distilled water.

The 64 per cent hydrazine solution and the 45 per cent potassium hydroxide solution are standard mixtures and are commercially available from the Matheson, Coleman, and Bell Company, as follows:

Item	Unit of Issue	Number	Price Estimate
1. Potassium Hydroxide, Reagent, 45% solution	8 pints	PX1488,CB1150	\$ 8.64
2. Hydrazine, practical, 64% in water	500 grams	HX541,P6759	\$ 7.20

It requires approximately 8 pints of the potassium hydroxide solution and 500 grams of the hydrazine solution to mix one 5 liter fuel batch (10-33 Solution).

Other mixtures can be obtained by computing the per cent by volume of each ingredient.

EXAMPLE: 10-33 Fuel Batch

160 ml x .64 = 102 ml pure N_2H_4

160 ml x .36 = 58 ml H_2O

740 ml x .45 = 332 ml pure KOH

740 ml x .55 = 408 ml H_2O

100 ml H_2O

$$\gamma_H = \frac{102}{1000} \times 100 = 10.2\% \quad 1000 \text{ ml} = \text{Total Volume}$$

$$\gamma_E = \frac{332}{1000} \times 100 = 33.2\%$$

A table of one liter batches convenient for examining the effect of changing γ_H and γ_E is shown below.

Fuel Batch	ml of 64% N_2H_4 solution	ml of 45% KOH solution	ml of distilled H_2O
5-33	78	740	172
10-33	160	740	100
15-33	235	740	25
5-20	78	445	477
10-20	160	445	395
15-20	235	445	320

CHEMICAL SAFETY PRECAUTIONS: The following precautions should be taken when handling fuel cell chemicals:

1. Work in an open or ventilated space.
2. Wear eye protection, rubber gloves and a rubber apron.
3. Work near a sink with running water.
4. Avoid skin contact with fuel cell chemicals. KOH can cause dangerous burns. N_2H_4 can also cause burns. N_2H_4 is toxic and has an accumulative effect. Neither is dangerous if washed off immediately. Both chemicals are bases and can be washed away quickly with a towel wetted with dilute acetic acid (vinegar) accompanied by flushing thoroughly with water. Any contact with the eyes or open cuts may be more dangerous. Flush the area thoroughly as described and consult a doctor immediately if this occurs.
5. Avoid sniffing fumes, as they are toxic. Use a fan to blow fumes away from mixing area.
6. Pour carefully and insure that all chemical bottles are tightly closed immediately after use.
7. THE ANTIDOTE FOR INTERNAL HYDRAZINE POISONING IS AS FOLLOWS: Give a tablespoon full of salt in warm water to induce vomiting. Cause vomiting until the liquid is clear. Give one ounce of charcoal (burnt toast). Mix and give the "Universal Antidote" as follows:

2 parts charcoal (burnt toast)

1 part tannic acid (strong tea)

1 part magnesium oxide (milk of magnesia)

Mix together in warm water.

CALL A DOCTOR IMMEDIATELY.

8. THE ANTIDOTE FOR INTERNAL POTASSIUM HYDROXIDE POISONING IS AS FOLLOWS:

   Give large amounts of vinegar or citrus juices. Follow with olive oil.

   CALL A DOCTOR IMMEDIATELY.

9. FOR EYE CONTACT WITH EITHER CHEMICAL:

   Wash immediately with very large amounts of fresh water. Wash with a 5 per cent boric acid solution. CALL A DOCTOR IMMEDIATELY.

10. FOR SKIN CONTACT WITH EITHER CHEMICAL:

    Wash immediately with very large amounts of fresh water. Flush the area with dilute acetic acid (vinegar). Wipe away the "slippery" base with a towel wetted with dilute (5 per cent) acetic acid or vinegar. CALL A DOCTOR IF CONTACT OVER A LARGE SKIN AREA IS MADE, OR IF STINGING OR BURNING SENSATION PERSISTS.

Hydrazine in the fuel batch is used at the rate of 47 ml per hour per cell for a current load of 75 amperes. Water is produced as a by-product of the chemical reaction at the rate of 45 ml per hour per cell for the same load current. The fuel battery in the Fuel Cell Research System contains 4 cells. (See Figure 4) [2]

As the hydrazine in a fuel batch is used, the cell voltage output will begin to decrease. This effect will become noticeable after two to three hours of operation on one six liter fuel batch. Hydrazine may be added to replenish the system providing that γ_H does not exceed 15 per cent. The high level warning light on the front panel will indicate when the fuel tank level is too high. When this light

comes on, no further liquid should be added. Knowing the hours of operation on one fuel batch, the average load current, and the rough values of hydrazine consumption and water production, the amount of 64 per cent hydrazine which can be added to the fuel tank can be computed.

<u>EXAMPLE:</u> Six liters of 10-33 fuel solution have been in for two hours at an average load current of 20 amps. How many ml of 64 per cent hydrazine solution may be added such that $10 < \gamma_H < 13$?

$$-\frac{20}{75} \times 47 = -12.5 \text{ ml } N_2H_4/\text{cell/hr.}$$

$$+\frac{20}{75} \times 45 = +12.0 \text{ ml } H_2O/\text{cell/hr.}$$

For 6 liters of 10-33 fuel solution, there are 600 ml of pure hydrazine in the initial solution.

$$600 \text{ ml} - 12.5 \frac{\text{ml}}{\text{cell-hr}} \times 4 \text{ cell} \times 2 \text{ hrs} = 500 \text{ ml}$$

There are 3420 ml of H_2O in the initial 6 liters of the 10-33 fuel solution.

$$3420 \text{ ml} + 12.0 \frac{\text{ml}}{\text{cell-hr}} \times 4 \text{ cells} \times 2 \text{ hrs} = 3516 \text{ ml}$$

The initial 6 liters of 10-33 fuel solution contained 1980 ml of pure KOH. This value should not be changed by the fuel cell operation.

After two hours of operation, there are 500 ml of pure N_2H_4, 3516 ml of H_2O, and 1980 ml of pure KOH. Therefore,

$$\gamma_H = \frac{500}{5996} \times 100 = 8.35\%$$

$$\gamma_E = \frac{1980}{5996} \times 100 = 33.1\%$$

If 500 ml of 64 per cent N_2H_4 were added:

$500 \times .64 = 320$ ml pure N_2H_4

$500 \times .36 = 180$ ml H_2O

$$\gamma_H = \frac{500 + 320}{5996 + 500} = \frac{820}{6496} = .126 \text{ or } 12.6\%$$

$$\gamma_E = \frac{1980}{6496} = .305 \text{ or } 30.5\%$$

IIIE. Maintenance:

In order to maintain the Fuel Cell Research System in proper working order, the following action should be taken.

1. Weekly Maintenance Runs: Light off the system and run it under loaded conditions for ten minutes. Use a load which will draw 10-15 amperes. This must be done a minimum of once a week, and preferably twice a week. If the system is run for an experiment, this is the equivalent of a maintenance run.
2. Weekly Field Day: Check the entire stand for moisture. Wipe up with a towel wetted with dilute acetic acid (5 per cent) or vinegar.
3. Weekly Circuit Check: Trace all circuits shown in Appendix II. Check for loose fittings on the liquid and gas circuitry. Check for grounds, shorts, or dangerous wire exposures in the 115 volt electrical circuit as well as the fuel cell output circuit. Keep the system free of excess equipment or tools which may interfere with its operation.
4. If the system is not to be used for a period of two weeks or more, carry out the storage shut down procedure found in Section D of Appendix III.
5. Quarterly Cleaning of Electrodes: The storage shut-down procedure found in Section D of Appendix III should be carried out at least once every three months. This causes a purging of all active chemicals from the system.
6. If the fuel cell electrodes become excessively exposed to air while the cell is not in operation, it will cause a coating of the electrodes. This may occur after a storage period. This coating will result in a reduced fuel cell power output. It will correct itself by running the system normally. If the rated power cannot be obtained after ten hours of operation, investigate other causes of reduced power.

7. The 45 per cent KOH solution in the air scrubber should be replaced after ten hours of use, and at least once a quarter.
8. The dilute acetic acid solution (5 per cent) in the fuel tank exhaust scrubber and the byproduct collector should be replaced after ten hours of operation, and at least once a quarter.
9. It is important not to let excess moisture collect in the fuel cell. Thus, purging, or blowing gas through the fuel cell before and after each operation, is part of the operating procedures. If excess moisture is noted in the oxygen source outlet, blow oxygen through the fuel cell and force this moisture into the byproduct collector. This will be a part of the weekly maintenance run. However, it can be done without lighting off the entire system if excess moisture is noted.
10. Trouble-Shooting: The Fuel Cell Instruction Manual contains procedures for trouble-shooting. [2] The following gentleman was helpful in correspondence concerning the system.

    Mr. Eugene Revolinsky
    Manager, Application Services
    Research Division
    Allis-Chalmers
    Box 512
    Milwaukee, Wisconsin 53201

11. Operators should be thoroughly familiar with the Fuel Cell Instruction Manual. [2] CONSISTENT AND ACCURATE ENTRIES IN THE OPERATORS LOG ARE ESSENTIAL TO PROPER MAINTENANCE.
12. A list of equipment making up the Fuel Cell Research System is found in Appendix I of the Fuel Cell Instruction Manual. [2] The following items of this list were <u>not</u> used: Mechanical System (6), (10), (12), (13) and (14). Electrical Components (2), (6), (12) and (13). All meters, shunts, and resistors were obtained from on hand items. Materials

may be ordered from:

Allis-Chalmers
Box 512
Milwaukee, Wisconsin 53201

13. The current-pressure transducer was obtained from the Foxboro Company. [11] Parts and other types of control valves may be ordered from:

The Foxboro Company
399 Preda Street
San Leandro, California 94577

Another source of control valves is:

Fisher Governor Company
Marshalltown, Iowa 50158

The current-pressure transducer cover should be removed occasionally and the parts cleaned. See the Foxboro Instruction Manual for adjustment and calibration procedures. [11]

14. The brass and nylon fittings, polyethylene tubing, and rubber tubing was manufactured by:

Imperial Eastman Corporation
6300 W. Howard St.
Chicago, Illinois

This corporation's products are handled by the California Equipment Company, San Francisco, California. Some of the items can be purchased locally at Peninsula Auto Parts, Monterey, California, and orders can be placed there for items not in stock.

15. Other materials used include:

Stainless steel tubing

Teflon tape for sealing fittings and joints

Pyrex bottles, obtained from the Chemistry Department

Hose clamps, obtained at Peninsula Auto Parts

16. The stand and associated fittings were constructed by Mr. Frank B. Abbe, Machinist, of the Naval Postgraduate School

Machine Facility. This Facility should be contacted for repairs or construction of parts required in further experiments.

17. SAFETY NOTE: WHEN TROUBLE-SHOOTING FOR FUEL LEAKS, WEAR EYE PROTECTION, RUBBER GLOVES AND RUBBER APRON TO PROTECT AGAINST CHEMICAL SPILLAGE.

IIIF. Operation Log:

The Operation Log should be a three ring, loose-leaf binder with the following sections:

1. A list of personnel checked out in operating the system.
2. A copy of Appendices I, II, and III of this thesis.
3. A copy of the Allis-Chalmers Fuel Cell Instruction Manual.
4. An operation record kept on pages which are copies of Figure III-1. One such page should be filled out for each time the system is operated.
5. A maintenance log, kept on plane lined paper. It should be a chronological record of casualties, major maintenance items, and general items of interest. Weekly maintenance runs need not be entered, but any storage procedure carried out should be noted.

The Operation Log should be reviewed periodically by the student using the system for a project, or by the Professor responsible for the system.

Date:	Start:	Stop:	Time for this run:

Fuel Batch	Date Mixed	ml 64% N_2H_4	ml 45% KOH	ml H_2O	Run Time this Batch
Initial Mixture					
Amounts added to fuel batch					

Date Fuel Batch Drained: ______

Was storage procedure carried out? ______

Date 45% KOH in air scrubber last replaced: ______

Date 5% acetic acid solution in the byproduct collector and the fuel tank scrubber replaced: ______

Date fuel cell last run: ______

Are weekly maintenance runs being held? ______

Oxygen source used: ______ Air ______ Pure oxygen ______ Mixture

Comments on gas input:

______

	Volts	Amperes	Watts
Average values fuel cell output			
Maximum values fuel cell output			

Type of load used:

______

Total accumulative hours of operation to date: ______

Comments on operation:

______

Operator's signature

EMERGENCY SHUT-DOWN: 1) MAIN 115V. POWER OFF 2) MAIN COMPRESSED GAS VALVE CLOSED.

NEUTRALIZE CHEMICALS: FLUSH WITH FRESH WATER AND DILUTE ACETIC ACID OR VINEGAR.

Figure III-1
Fuel Cell Operation Record

APPENDIX IV

LABORATORY PROCEDURES

IVA. Fuel Cell Chemical Parameter Analysis:

Purpose: To examine changes in the output voltage caused by varying some parameters of the fuel cell chemical inputs.

Reference: Sections 3 through 13, Appendices I, II, and III of the Naval Postgraduate School thesis entitled "Experimental Modeling and Control of the Hydrazine-Oxygen Fuel Cell", by LT Robert C. Powers, USN, June 1967.

Equipment:

1. Fuel Cell Research System described in the reference.
2. Two direct current voltage sources, with a variable voltage control.
3. One adjustable carbon pile load bank with high current leads.
4. Chemicals required to run the fuel cell.
5. One 100 degree centigrade thermometer.
6. One voltage x-y plotter or trace recorder.

Procedure:

1. Read the reference, with particular attention to Appendix III. CAREFULLY OBSERVE ALL SAFETY PRECAUTIONS.
2. Set up a compressed air input to pass through the air scrubber and into the current-pressure transducer.
3. Put the variable voltage DC source on the middle shelf of the Fuel Cell Research System, and plug it into the auxilliary power panel. Run leads to the current-pressure transducer input. The current-pressure transducer has a resistance of about 170 ohms. A current of zero to fifty miliamperes will correspond to an output pressure of approximately zero to twenty-five psig.
4. Make sure that the load switch is in the OFF position. Plug the high current leads from the carbon pile load into the fuel cell output terminals.

5. Locate the voltage recorder and plug it in to the auxilliary panel. Connect the recorder so as to measure the fuel cell voltage output. If a very sensitive voltage change is to be detected, the voltage recorder may be biased to permit selection of a sensitive scale. Use another variable voltage DC source and connect it between the fuel cell output and the recorder so as to bias the fuel cell output voltage to the recorder range.

6. Carry out the light-off procedure contained in Appendix III of the reference.

7. The following table lists the parameters to be examined and the primary means of controlling its value.

Parameter	Control
a) Temperature (T_{FC})	Fuel tank thermostat
b) Air pressure (P_A)	Input to current-pressure transducer
c) Air flow rate (F_A)	Oxygen source output orifice control valve
d) Hydrazine fuel pressure (P_H) and flow-rate (F_H)	Fuel pump motor controller
e) Per cent hydrazine in fuel mixture (γ_H)	Manual changing of mixture
f) Per cent electrolyte in fuel mixture (γ_E)	Manual changing of mixture

Each of the above parameters should be varied over a sufficient range to notice a change in the voltage output. Make a plot of voltage output (V) vs. each parameter. Discuss the physical cause of the voltage output change for at least one parameter.

Note: DO NOT EXCEED 25 psig input pressure or 75 degrees centigrade operating temperature.

8. Turn off the fuel pump and the fuel tank heaters. Close the main valve on the compressed air tank. Close all valves in the pneumatic circuitry.

9. Set up a pure oxygen input to pass directly into the current-pressure transducer. Open valves to the current-pressure

transducer and adjust control to permit oxygen to enter the fuel cell.

10. Repeat step (7) for a pure oxygen input.
11. In order to examine per cent oxygen in the oxygen source (γ_o), leave the pure oxygen input as before and connect a pure nitrogen source to the auxilliary input. Adjust the micrometer valves at the point where the two gases will mix. Mixing can be obtained by setting a constant nitrogen pressure, adjusting the orifice on the oxygen line to a small opening, and varying the current to the current-pressure transducer. The oxygen pressure at the small orifice will then determine how much oxygen is permitted to enter the nitrogen stream. γ_o can be calculated by comparing the pressures and flow rates on each gas line, and on the fuel cell input line.
12. Carry out the shut-down procedures contained in Appendix III of the reference.
13. Plot γ_o vs. V from the data obtained. Discuss γ_o as a fuel cell control parameter.

IVB. Fuel Cell Load and Internal Resistance Analysis:

Purpose: To examine the load and internal resistance characteristics of a fuel cell system.

Reference: Sections 3 through 13, Appendices I, II, and III of the Naval Postgraduate School thesis entitled "Experimental Modeling and Control of the Hydrazine-Oxygen Fuel Cell", by LT Robert C. Powers, USN, June 1967.

Equipment:

1. Fuel Cell Research System described in the reference.
2. Chemicals required to run the fuel cell.
3. One adjustable carbon pile load bank, with high current leads.
4. One variable voltage DC power source.

Procedure:

1. Read the reference, with particular attention to Appendix III. CAREFULLY OBSERVE ALL SAFETY PRECAUTIONS.
2. Set up a compressed air input to pass through the air scrubber and into the current-pressure transducer.
3. Put the variable voltage DC source on the middle shelf and plug it into the auxilliary power panel. Set up leads to control the current-pressure transducer. (See Appendix IVA)
4. Make sure that the load switch is in the OFF position. Plug the high current leads from the carbon pile load into the fuel cell output terminals.
5. Carry out the light-off procedure contained in Appendix III of the reference. Use fuel mixture 10-33.
6. With the air input pressure at 3 psig, flow meter at a reading of 6, and fuel pump motor at maximum speed, set the fuel tank heater thermostat in the middle of its range. With these parameters constant, vary the fuel cell load using the carbon pile resistor. Record the following for at least ten values of the load resistance: Open circuit voltage (E), load voltage (V), and load current (I). Compute the

following: Power (W), load voltage (R_L), and fuel cell internal resistance (R_g). Repeat this procedure for input pressure (P_A) values of 10 and 15 psig.

7. Plot output power (W) vs. load resistance (R_L) for P_A equal to 3, 10, and 15 psig.
8. Calculate the values of R_g for P_A equal to 3, 10 and 15 psig.
9. For what value of load resistance does maximum power occur? How does this compare with the values of R_g calculated? Discuss.
10. Repeat steps (6), (7), (8) and (9) using a pure oxygen input. This may also be done for some chosen value of γ_o using a gas mixing process such as that discussed in Part A of Appendix IV.
11. The value of per cent hydrazine in the fuel mixture (γ_H) will have decreased while carrying out the first part of this experiment. Repeat steps (6), (7), (8) and (9) for an air pressure input. Compare the curves obtained with those which resulted from the first test, noting the effect of decreasing γ_H. Using the procedure discussed in Part D of Appendix III, compute the approximate value of γ_H which existed during the last test.
12. Carry out the shut-down procedures contained in Appendix III of the reference.
13. Discuss a possible steady-state model for the fuel cell.

IVC. Fuel Cell Frequency Analysis:

Purpose: To examine the frequency response of a fuel cell, and obtain a mathematical model of its operation.

Reference: Section 15, and Appendices I, II and III of the Naval Postgraduate School thesis entitled "Experimental Modeling and Control of the Hydrazine-Oxygen Fuel Cell", by LT Robert C. Powers, USN, June 1967.

Equipment:

1. Fuel Cell Research System described in the reference.
2. Chemicals required to run the fuel cell.
3. One adjustable carbon pile load bank, with high current leads.
4. Three variable voltage DC power sources.
5. One dual trace recorder capable of sensing voltage changes as low as hundredths of volts.
6. Amplifiers for the dual trace recorder.
7. One 2N736 Transistor, or a similar type.
8. Two 1K resistors.
9. Peg board and leads.
10. One sine wave generator.

Procedure:

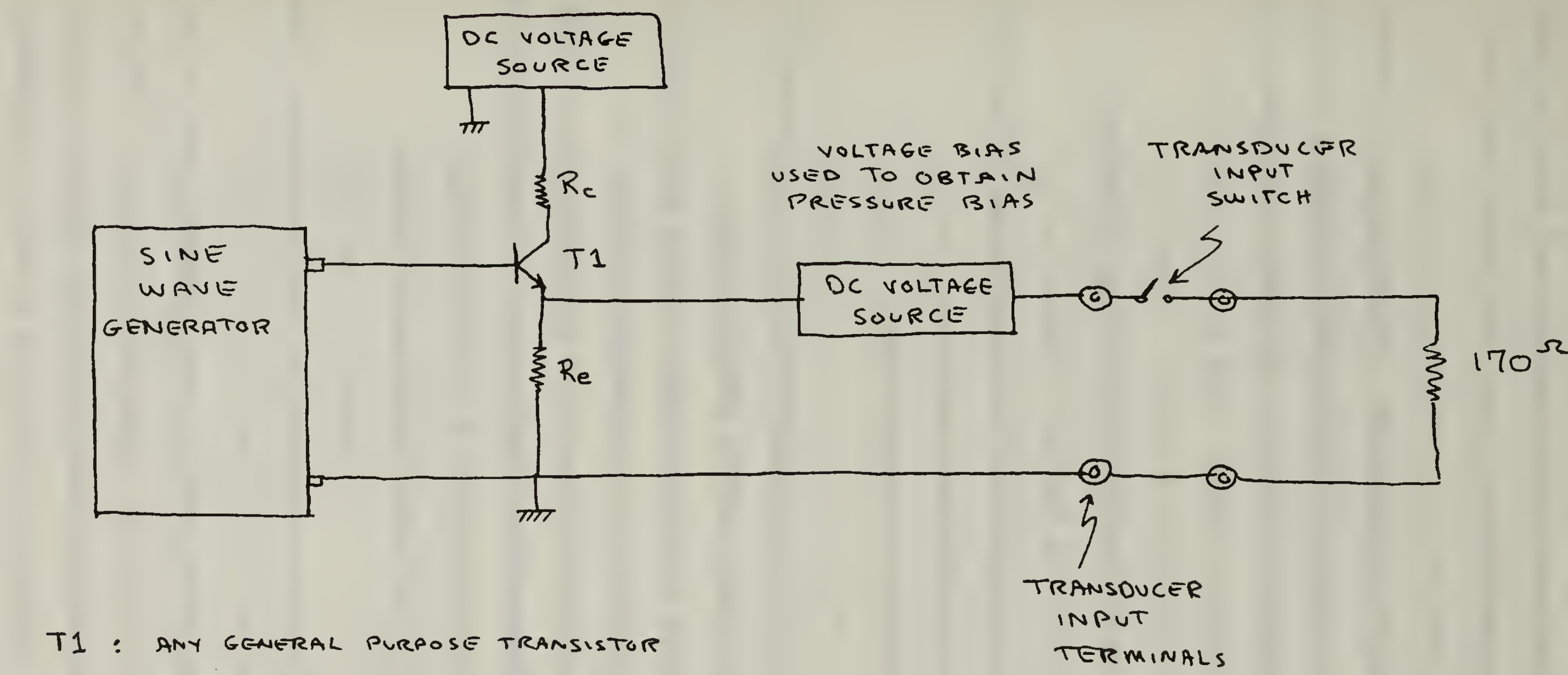
1. Read the reference, with particular attention to Appendix III. CAREFULLY OBSERVE ALL SAFETY PRECAUTIONS.
2. Set up a compressed air input to pass through the air scrubber and into the current-pressure transducer. NOTE: The frequency analysis is to be done with an air input only, with P_A as the control parameter. Procedures for frequency analysis of other parameters will require a different set-up.
3. Arrange the equipment on the middle shelf of the Fuel Cell Research System. Put the load leads into the fuel cell output terminals.
4. The following is a description of the circuit required as an input to the current-pressure transducer. The sine wave

generator should lead into a small, one transistor amplifier. This amplifier will lead into a DC voltage source which will be used to bias the pressure. This DC voltage source will lead into the current-pressure transducer, with a return to a common point in the circuit. Thus, the bias voltage causes an output pressure, about which can be generated a sinusoidal output pressure caused by the voltage sine wave generator. This circuit is pictured in Figure IV-1.

5. Arrange the dual trace recorder such that a trace of the current-pressure transducer input voltage and a trace of the fuel cell output voltage are obtained. It may be necessary to put a negative bias on the trace recorder in order to obtain the necessary voltage scale. The current-pressure transducer input voltage trace will be taken as the pressure input and should be labeled in psig. (This assumes that the current-pressure transducer has a constant transfer function.)
6. Carry out the light-off procedure found in Appendix III. Vary the sinusoidal input pressure frequency from .01-3.0 cycles per second, recording the input and output traces described in (5).
7. Use the traces obtained to determine amplitude and phase relationships, and plot the output/input in decibels vs. the base ten log of radian frequency (Bode Plot).
8. Obtain several Bode Plots and average them. Plot an average frequency response for the fuel cell. Does the phase curve indicate the presence of a time delay?
9. Using standard pole/zero techniques, determine a fuel cell transfer function.
10. Note: This frequency analysis may be done for any pressure bias or starting conditions desired. See Appendix I of the reference for a suggested set-up.
11. For several runs, note the effect on the frequency response

of the decrease of γ_H with operating time.

12. Does changing the value of B_p, the pressure bias, or A_p, the input pressure amplitude affect the frequency response?
13. Carry out normal shut-down procedures contained in Appendix III of the reference.
14. Take the experimentally determined transfer function and make a Bode Plot. Discuss the use of this transfer function in examining a feedback control system for the fuel cell.



T1 : ANY GENERAL PURPOSE TRANSISTOR

R_c AND R_E : SELECT FOR BEST OPERATION. VALUES OF ABOUT ONE KILLOHM WILL WORK.

FIGURE IV-1

TRANSDUCER INPUT CIRCUIT

IVD. Fuel Cell Transient Analysis:

Purpose: To examine the step response of the fuel cell to a pressure input, compare it with that predicted by a fuel cell model, and note any delay time effects.

Reference: Sections 16 and 17, Appendices I, II and III of the Naval Postgraduate School thesis, entitled "Experimental Modeling and Control of the Hydrazine-Oxygen Fuel Cell", by LT Robert C. Powers, USN, June 1967.

Equipment:

1. Fuel Cell Research System described in the reference.
2. Chemicals required to run the fuel cell.
3. One adjustable carbon pile load bank, with high current leads.
4. One variable voltage DC power source.
5. One dual trace recorder, with amplifiers.

Procedure:

1. Read the reference, with particular attention to Appendix III. CAREFULLY OBSERVE ALL SAFETY PRECAUTIONS.
2. Set up a compressed air input to pass through the air scrubber and into the current-pressure transducer. NOTE: The transient analysis is to be done with an air input only, with P_A as the control parameter. Procedures for transient analysis of other parameters will require a different set-up.
3. Connect the carbon pile load to the fuel cell output terminals.
4. Connect the DC voltage source to the current-pressure transducer input.
5. Set up the dual trace recorder so as to obtain a trace of the current-pressure transducer input and the fuel cell voltage output. (Assume that the current-pressure transducer transfer function is a constant as was done in Part C of Appendix IV.)
6. Carry out the light-off procedure found in Appendix III.

7. Set P_A to 3 psig. Apply a step of from 3 to 5 psig, recording both the input and output described in (5). Do the same for 3-7 psig, 5-7 psig, and 5-9 psig.

8. What is the overshoot of the fuel cell step response? The settling time? How does the response compare with what could be predicted from using the mathematical model obtained from the frequency analysis? Discuss.

9. Set P_A to 10 psig. Apply a negative step input which reduces P_A to zero. Record the fuel cell output decay.

10. Set P_A to 10 psig. Apply a negative step input which reduces P_A to 5 psig.

11. Compare the results obtained in steps (9) and (10). Are these results which might be expected from the transfer function experimentally obtained from the frequency analysis? Discuss.

12. What causes the very slow decay of the fuel cell output voltage observed in the results of step (9)?

13. Set P_A to 3 psig and obtain a steady state running condition. Set P_A equal to zero for a time t_{po}. Then, apply an input pressure step of zero to three psig. Record the input step and the output response. Note the delay time between (t_d) between the input and the output, and the overshoot of the output. Do this for values of t_{po} equal to 30, 60, 120, 240, 360 and 600 seconds.

14. Plot t_{po} vs. t_d and overshoot. Discuss the observed effect.

15. How does the time delay observed here compare with that obtained by constructing the phase curve of the frequency analysis? Discuss.

16. Carry out the shut-down procedures found in Appendix III.

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13. ABSTRACT

Fuel cells are direct energy conversion devices which produce direct current electrical power. They are being considered for use in many modern power applications such as spacecraft, vehicular propulsion, and general purpose electrical power. The hydrazine-oxygen fuel cell is one of several types, and its operation is described. Some parameters of the chemical inputs, such as oxygen source pressure, are experimentally tested and discussed as candidates for controlling the output voltage. A control parameter is selected, and a mathematical model of the fuel cell is developed. A "Fuel Cell Research System", designed and constructed by the author, is described and operating instructions are presented.

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